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DESIGN REQUIREMENTS FOR MUNICIPAL DIATOMITE FILTERS

Paul E. Morgan, et al

Iowa Engineering Experiment Station
Ames, Iowa

15 December 1965

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THIRD
PROGRESS REPORT

March 1, 1964, through November 30, 1965
(21 months)

DESIGN REQUIREMENTS FOR MUNICIPAL DIATOMITE FILTERS

Project 549S
Iowa Engineering Experiment Station
Iowa State University
Ames, Iowa

U. S. Public Health Service
Division of Water Supply and Pollution Control
Research Grant - WP 00196

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U. S. Public Health Service
Division of Water Supply and Pollution Control
Research Grant WP 00196

DESIGN REQUIREMENTS FOR MUNICIPAL DIATOMITE FILTERS

PRINCIPAL INVESTIGATORS: PAUL E. MORGAN
E. ROBERT BAUMANN

Third Progress Report
March 1, 1964 through November 30, 1965
(21 months)

Iowa State University of Science and Technology
Engineering Experiment Station
Ames, Iowa

Details of illustrations in
this document may be better
studied on microfiche

December 15, 1965

SUMMARY PAGE

RESEARCH GRANT NO: WP-00196 Design Requirements for Municipal Diatomite Filters.

PRINCIPAL INVESTIGATORS: Paul E. Morgan
E. R. Baumann

NAME OF SPONSORING INSTITUTION:
Iowa Engineering Experiment Station
Iowa State University
Ames, Iowa 50010

PERIOD COVERED BY REPORT:
March 1, 1964 through November 30, 1965

DATE OF PREPARATION OF REPORT:
December 15, 1965

SUMMARY STATEMENT

This study was undertaken to determine the characteristics of municipal applications in which diatomite filters may be used successfully, to study the effect of various variables on filtration economy and effectiveness, and to outline a procedure for designing a plant to operate with maximum economy. Diatomite filtration equations have been developed to predict the head loss-time relationship during a filter run by use of empirical filter cake resistance measurements. An equation has been developed to predict filter cake resistance from measureable filtration variables. Empirical constants in the prediction equation are collected in pilot filter runs. A digital computer program has been prepared to use the equations and cost information to optimize plant design.

Filter cake resistance information has been collected in laboratory and plant-scale filtration work on iron bearing, clay bearing, and lime-softened waters. Additional laboratory and field work is necessary to collect additional filter cake resistance data on coagulated and uncoagulated surface waters. These data will be used to evaluate the characteristics of municipal installations where diatomite filters may be used economically.

Laboratory studies are being conducted to determine the effect of inorganic metal coagulant coatings and organic polyelectrolyte coatings on the zeta potential of diatomite particles and on the changes in filter cake resistance that result from the coatings. Depending on conditions, the zeta potential may be changed from electronegative to electropositive, and cake resistance may be increased or decreased. The change in filtration effectiveness is now under study.

STAFFING

PROFESSIONAL PROJECT PERSONNEL:

May 1, 1964 through November 30, 1965

	Name	Title	Period	% of Time on Project	Source of Support
1.	Paul E. Morgan,	Prof.	May 64-Dec 65	10%	Univ funds
2.	E. Robert Baumann, Ph.D.,	Prof.	May 64-Dec 65	25%	Univ funds
3.	John L. Cleasby, Ph.D.,	Prof.	May 64-July 65	22.5%	Grant funds
			July 65-Dec 65	18.75%	Grant funds
4.	Charles S. Oulman, Ph.D.,	Asst. Prof.	May 64-July 64	17.5%	Grant funds
			July 64-July 65	12%	Grant funds
			July 65-Dec 65	25%	Grant funds
5.	P. Regunathan,	Res. Grad. Asst.	May 64-Dec 65	50%	Grant funds
6.	Thomas Besett,	Res. Grad. Asst.	Dec 64-Dec 65	50%	Grant funds
7.	Kou-Ying Hsiung,	Res. Grad. Asst.	Sept 64-Jan 65	50%	Grant funds
8.	Donald E. Burns,*	Grad. Student	May 64-Dec 65	25%	USPHS Fellowship
9.	James H. Dillingham,*	Grad. Student	May 64-Aug 65	50%	USPHS Fellowship
10.	Kenneth E. Merideth,*	Grad. Student	Dec 64-Dec 65	25%	USPHS Fellowship
11.	Lawrence L. Olson,*	Grad. Student	Dec 64-Dec 65	25%	USPHS Traineeship

FOREIGN TRAVEL: None

* These personnel were graduate students in sanitary engineering who elected to conduct their research in diatomite filtration of water. Their research expenses were supported in part by the grant. Burns is continuing Ph.D. research in this area.

VITA

ADDITIONAL PROFESSIONAL PERSONNEL

Note: Biographical sketches for P. E. Morgan, E. R. Baumann, J. L. Cleasby, C. S. Oulman, J. H. Dillingham, B. B. Hall, and J. L. Hawley were included in the Application for Research Grant (WP-00196-04). Additional biographical sketches for Perialwar Regunathan and D. E. Burns were included in the SECOND PROGRESS REPORT (April 30, 1964).

NEW PERSONNEL

Thomas M. Besett

Born: Sioux City, Iowa (September 26, 1940)
Graduated:
Iowa State University, B.S. (Civil Engineering). May, 1964
Iowa State University, M.S. (Sanitary Engineering), May, 1966)*

* Currently a research graduate assistant supported by grant funds working on his M.S. degree to be awarded in May, 1966.

Kou-Ying Hsiung

Born: Feng-yang, Anwhei, Republic of China (January 4, 1920)
Graduated:
Tang-shan Engineering College,
Chiao-Tang University (Ping Yueh, Kwerchoco, China)
B.S. (Civil Engineering), June, 1943.
Johns Hopkins University, M.S. (Civil Engineering) June, 1960.
Experience:

Director, Taiwan Public Works Bureau	1958-1964
Chief, Tamsui River Bridge	1956-1958
Managing Director, Taiwan Railway Admm.	1949-1956

Currently, Research Graduate Assistant on a doctoral program. He is supported with State Funds in sand filtration research.

Kenneth C. Merideth

Born: Keokuk, Iowa (May 15, 1942)
Graduated:
Iowa State University, B.S. (Civil Engineering), November, 1964
Iowa State University, M.S. (Sanitary Engineering), May, 1966)*

* Currently a U.S.P.H.S. (WSPC) Research Fellow working on an M.S. degree to be awarded in 1966. His M.S. research is concerned with studies of the effect of feeding methods on the particle size and hydraulic characteristics of diatomite.

Larry Lee Olson

Born: Rudd, Iowa (November 13, 1942)
Graduated:
Iowa State University, B.S. (Civil Engineering), 1964
Iowa State University, M.S. (Sanitary Engineering), (May, 1966)*

* Currently a U.S.P.H.S. (WSPC) Trainee working on his M.S. degree to be awarded in May, 1966.

LIST OF PUBLICATIONS ON DIATOMITE AND SAND FILTRATION

DIATOMITE

Supported by PHS Research Grant WP-00196, Division of Water Supply and Pollution Control

1. Cleasby, John L. Turbidimetric control of filter effluent quality. Journal A.W.W.A., 52: 11, p 1411-1415, November, 1960.

2. LaFrenz, R. L. and E. R. Baumann. Optimums in diatomite filtration. Journal A.W.W.A., 54: 7, p 847-851, July, 1962.

3. Baumann, E. R., Cleasby, J. L. and R. L. LaFrenz. A theory of diatomite filtration. Journal A.W.W.A., 54: 9, p 1109-1119, September, 1962.

4. Baumann, E. R. and R. L. LaFrenz. Optimum economical design for municipal diatomite filtration plants. Journal A.W.W.A., 55: 1, p 48-58, January, 1963.

5. Baumann, E. R. and C. S. Oulman. Iowa State: Pilot studies of diatomite filtration. Water Works Engineering, 116: 5, p 366-368, May, 1963.

6. Baumann, E. R. and C. S. Oulman. Modified form of diatomite filtration equation. Journal, A.W.W.A., 56: 3, p 330-333, March, 1964.

7. Oulman, C. S. and E. R. Baumann. A plastic microelectrophoresis cell for zeta potential measurements. Journal, Water Pollution Control (in press-Industry Idea Clinic, 1963 Annual Meeting).

8. Oulman, C. S. and E. R. Baumann. A photoelectric settlimeter for sedimentation studies. Journal, Water Pollution Control (in press-Industry Idea Clinic, 1963 Annual Meeting).

9. Oulman, C. S. and E. R. Baumann. Streaming potentials in diatomite filtration of water. Journal, A.W.W.A., 56: 7, p 915-930, July, 1964.

10. Dillingham, James H. and E. R. Baumann. Hydraulic and particle size characteristics of some diatomite filter aids. Journal, A.W.W.A., 56: 6, 793-808, June, 1964.

11. Baumann, E. R., Cleasby, J. L. and P. E. Morgan. Theoretical aspects of diatomite filtration. Water and Sewage Works, Part I, 111: 229-233, May, 1964. Part II, 111: 290-294, June, 1964. Part III, 111: 331-336, July, 1964.

Misc. Baumann, E. R. Pure water while you wait. The American City, p 23, December, 1963.

12. Oulman, C. S., D. E. Burns, and E. R. Baumann. "Effect on filtration of polyelectrolyte coatings of diatomite filter media", Journal, A.W.W.A., 56: 9, p 1233-1238, September, 1964.

13. Baumann, E. R., J. L. Cleasby and P. E. Morgan. "Fundamentals of diatomite filter design", Proceedings of Conference on Filtration, University of Missouri, Rolla, Mo., April 7, 1965.

SAND

Supported by the Iowa Engineering Experiment Station

14. Cleasby, J. L. and E. R. Baumann. Selection of sand filtration rates. Journal A.W.W.A., 54: 5, p 579-602, May, 1962.

Note: This paper was presented the PUBLICATIONS AWARD in 1962 by the American Water Works Association "for the most notable contribution to the science of public water supply development published by the Association".

15. Cleasby, J. L. and E. R. Baumann. Selection of optimum filtration rates for sand filters. Iowa Engineering Experiment Station, Bulletin 198, January 24, 1962.

16. Cleasby, J. L. Single-stage softening permits filtration at 4 GPM/Square foot. Water Works Engineering, 115: 9, p 733, 767, 768, September, 1962.

17. Cleasby, J. L., Williamson, M. M., and E. R. Baumann. Effect of filtration rate changes on quality. Journal A.W.W.A., 55: 7, p 869-880, July, 1963.

18. Johnson, R. L. and J. L. Cleasby. The effect of backwash techniques on filter effluent quality. Journal, Sanitary Engineering Division, A.S.C.E. (Submitted July, 1965).

19. Baumann, E. R., Willrich, T. L., and D. D. Ludwig. For a purer water supply consider ---- Prechlorination. Agricultrual Engineering, 44: 3, p 138, March, 1963. (Condensation of ASAE Paper No. 62-208).

LIST OF PAPERS PRESENTED OR TO BE PRESENTED ON DIATOMITE FILTRATION

THIRD ANNUAL WATER QUALITY RESEARCH SYMPOSIUM, NEW YORK STATE DEPARTMENT OF HEALTH IN CONJUNCTION WITH NEW YORK WATER POLLUTION CONTROL ASSOCIATION AND NEW YORK SECTION AMERICAN WATER WORKS ASSOCIATION
March 24, 1966

1. Progress Toward Optimum Design of Diatomite Filters
   E. R. Baumann, J. L. Cleasby, and P. Regunathan
   (Lecture on latest developments in diatomite filter design)

JOHNS-MANVILLE CORP. DIATOMITE FILTRATION SEMINAR, CHICAGO, ILLINOIS
November 18, 1965

2. Least Cost Diatomite Filter Design - E. Robert Baumann
   (Lecture on Mathematical Model, Beta prediction and POPO)

TENTH SUMMER INSTITUTE IN WATER POLLUTION CONTROL, MANHATTAN COLLEGE, NEW YORK
June, 1965

3. Filtration - E. Robert Baumann
   (Lecture on theory of sand and diatomite filtration, factors affecting filter performances, design of filtration systems)

CONFERENCE ON FILTRATION, UNIVERSITY OF MISSOURI IN CONJUNCTION WITH THE MISSOURI SECTION OF THE AMERICAN WATER WORKS ASSOCIATION, ROLLA, MISSOURI
April 7, 1965

4. Fundamentals of Diatomite Filter Design
   E. R. Baumann, J. L. Cleasby, and Paul E. Morgan

NINTH SUMMER INSTITUTE IN WATER POLLUTION CONTROL, MANHATTAN COLLEGE, NEW YORK
June 23, 1964 (9-12 a.m.)

5. Filtration - E. Robert Baumann
   (Lecture on theory of sand and diatomite filtration, factors affecting filter performance, design of filtration systems)

84TH AMERICAN WATER WORKS ASSOCIATION ANNUAL CONFERENCE, TORONTO, CANADA
June 3, 1964 (Purification Division)

6. A.W.W.A. Task Group Report on Diatomite Filtration - E. Robert Baumann

June 2, 1964 (Committee on Research)

7. Use of Streaming Potentials in Filtration Research
   C. S. Oulman and E. R. Baumann
   (Paper presented by Dr. Oulman)

8. Coatings for Filter Media
   C. S. Oulman, Donald Burns, E. R. Baumann
   (Paper presented by E. R. Baumann)

1964 CONVENTION - EXPOSITION OF THE NATIONAL SWIMMING POOL INSTITUTE, CHICAGO, ILLINOIS

January 11, 1964

9. Theoretical Aspects of Diatomite Filtration
   E. R. Baumann, J. L. Cleasby, and P. E. Morgan
   (Paper presented by E. R. Baumann)

36TH ANNUAL MEETING OF WATER POLLUTION CONTROL FEDERATION, SEATTLE, WASHINGTON

October 9, 1963 (Industry Idea Clinic)

10. A plastic microelectrophoresis cell for zeta-potential measurements
    C. S. Oulman and E. R. Baumann
    (Paper presented by C. S. Oulman)

11. A photoelectric settlimeter for sedimentation studies
    C. S. Oulman and E. R. Baumann
    (Paper presented by E. R. Baumann)

18TH ANNUAL MEETING, IOWA SECTION, AMERICAN WATER WORKS ASSOCIATION, SIOUX CITY, IOWA

October 17, 1964

12. The Role of Zeta Potential in Coagulation and Filtration
    C. S. Oulman

83RD AMERICAN WATER WORKS ASSOCIATION ANNUAL CONFERENCE, KANSAS CITY, MISSOURI

May 21, 1963

13. Diatomite Filtration - E. Robert Baumann

82ND AMERICAN WATER WORKS ASSOCIATION ANNUAL CONFERENCE, PHILADELPHIA, PENNSYLVANIA

June 19, 1962

14. Theory of filtration applicable to diatomite filters
    E. R. Baumann and R. L. LaFrenz
    (Paper presented by E. R. Baumann)

1962 CONFERENCE OF STATE SANITARY ENGINEERS, WASHINGTON, D.C.

May 22, 1962 (Water Supply Workshop)

15. Use of Diatomite Filters for Public Water Supplies
    E. R. Baumann

JOHNS-MANVILLE WATER FILTRATION SEMINAR, MANVILLE, NEW JERSEY

December 12 and 13, 1961

16. University Research in Filter Aid Filtration
    E. R. Baumann

INTERNATIONAL WATER CONFERENCE OF THE ENGINEERS SOCIETY OF WESTERN PENNSYLVANIA, PITTSBURG, PENNSYLVANIA

October 23, 24, 25, 1961

17. Formal Invited Discussion of Paper by G. R. Bell entitled "Coagulant Coatings Open New Applications to Filter Aids"
    (Discussion by E. R. Baumann)

15TH ANNUAL MEETING, IOWA SECTION, AMERICAN WATER WORKS ASSOCIATION, DES MOINES, IOWA
October 21, 1960

18. Filtration Rate Research at Iowa State University
J. L. Cleasby

DEGREES AWARDED WHERE DIATOMITE FILTRATION RESEARCH EXPENSE WAS COMPLETELY OR PARTIALLY GRANT SUPPORTED

	Candidates	Degree	Date Awarded
1.	Robert L. LaFrenz	Ph.D.	June, 1961
2.	Charles S. Oulman	Ph.D.	February, 1963
3.	Mustafa S. Abdulrahman	Ph.D.	February, 1964
4.	James H. Dillingham	Ph.D.	November, 1965
5.	James H. Dillingham	M.S.	June, 1963
6.	James F. Hawley	M.S.	February, 1964
7.	Bruce B. Hall	M.S.	February, 1964
8.	Donald E. Burns	M.S.	December, 1964
9.	Perialwar Regunathan	M.S.	February, 1965
10.	John R. Harris	M.S.	May, 1965

DEGREES AWARDED WHERE RESEARCH WAS IN ASSOCIATED SAND FILTRATION AREA

1.	John L. Cleasby	Ph.D.	November, 1960
2.	Hugh Munson	M.S.	June, 1961
3.	Daniel D. Ludwig	Ph.D.	August, 1961
4.	Marvin M. Williamson	M.S.	June, 1962
5.	Robert L. Johnson	M.S.	August, 1963
6.	Norman Wenck	M.S.	June, 1963
7.	Kenneth J. Merry	M.S.	May, 1965
8.	David M. Fox	M.S.	August, 1965

THESES RESULTING FROM RESEARCH AT IOWA STATE UNIVERSITY IN DIATOMITE FILTRATION

Supported by Iowa Engineering Experiment Station

1. Philips, Eugene, Jr. Recommended practices for the design and operation of diatomite precoat filters. Unpublished Master of Science thesis, Iowa State University Library, Ames, Iowa, 1957.

Supported by PHS Research Grant RG-5958A (Small Grant Program) (September 1, 1958-August 30, 1959)

2. Miley, James F. Operation of pressure vs. vacuum diatomite filters using iron-containing water. Unpublished Master of Science thesis, Iowa State University Library, Ames, Iowa, 1959.

Supported by Iowa Engineering Experiment Station

3. Wiggers, R. G. Iron removal from natural and synthetic waters using diatomite filters. Unpublished Master of Science thesis, Iowa State University Library, Ames, Iowa, 1960.
4. LaFrenz, R. L. Effect of chemical coagulation on permeability of diatomite water filters. Unpublished Master of Science thesis, Iowa State University Library, Ames, Iowa, 1960.

Supported by PHS Research Grant WP-00196, Division Water Supply and Pollution Control (October 1, 1960-date)

5. LaFrenz, R. L. Design of municipal diatomite filters for iron removal. Unpublished Ph.D. thesis, Iowa State University Library, Ames, Iowa, 1961.
6. Oulman, C. S. Streaming Potentials in diatomite filtration of water. Unpublished Ph.D. thesis, Iowa State University Library, Ames, Iowa, 1963.
7. Dillingham, James F. Hydraulic and particle size characteristics of some diatomite filter aids. Unpublished Master of Science thesis, Iowa State University Library, Ames, Iowa, 1963.
8. Hall, Bruce B. Permeability of various grades of diatomite filter cake containing flocculent iron oxide. Unpublished Master of Science thesis, Iowa State University Library, Ames, Iowa, 1964.
9. Hawley, James F. Permeability of diatomite filter cakes containing various flocculent solids. Unpublished Master of Science thesis, Iowa State University Library, Ames, Iowa, 1964.
10. Abdulrahman, Mustafa S. Effect of ions in solution on the permeability of diatomite filter aids. Unpublished Ph.D. thesis, Iowa State University Library, Ames, Iowa, 1964.

11. Burns, Donald E. Coatings for filter media. Unpublished Master of Science thesis, Iowa State University Library, Ames, Iowa, 1964.

12. Regunathan, Perialwar. Permeability of diatomite filter cakes containing various clay minerals. Unpublished Master of Science thesis, Iowa State University Library, Ames, Iowa, 1965.

13. Harris, John R. Tertiary treatment of domestic wastes by chemical oxidation and/or diatomite filtration. Unpublished Master of Science thesis, Iowa State University Library, Ames, Iowa, 1965.

14. Dillingham, James H. Use of digital computer in design of diatomite filtration plants. Unpublished Ph.D. thesis, Iowa State University Library, Ames, Iowa, 1965.

THESES RESULTING FROM RESEARCH AT IOWA STATE UNIVERSITY IN SAND FILTRATION

Supported by PHS Research Grant RG-6755A (Small Grant Program)

1. Cleasby, John L. Selection of optimum filtration rates for sand filters. Unpublished Ph.D. thesis, Iowa State University Library, Ames, Iowa, 1960.

Supported by Iowa Engineering Experiment Station

2. Munson, Hugh. Iron removal vs. depth in a sand filter. Unpublished Master of Science thesis, Iowa State University Library, Ames, Iowa, 1961.

3. Williamson, Marcy. Effect of rate disturbances on the qualities of filtered water. Unpublished Master of Science thesis, Iowa State University Library, Ames, Iowa, 1962.

4. Wench, Norman. Evaluation of granular filters for contact water softening. Unpublished Master of Science thesis, Iowa State University Library, Ames, Iowa, 1963.

Supported by Iowa Engineering Experiment Station and City of Ames, Iowa

5. Johnson, Robert L. The effect of backwash techniques on effluent quality of sand filters. Unpublished Master of Science thesis, Iowa State University Library, Ames, Iowa, 1963.

Supported by Iowa Engineering Experiment Station

6. Ludwig, Daniel. Filtration and chlorination of small water supplies. Unpublished Ph.D. thesis, Iowa State University Library, Ames, Iowa, 1961.

Supported U.S.P.H.S. (WSPC) Fellowship Grants

7. Merry, Kenneth C. Tertiary treatment of domestic wastes by rapid sand filtration. Unpublished Master of Science thesis, Iowa State University Library, Ames, Iowa, 1965.

8. Fox, David M. Experimental evaluation of sand filtration theory. Unpublished Master of Science thesis, Iowa State University Library, Ames, Iowa, 1965.

PROGRESS REPORT IN SIX PARTS

SUMMARY STATEMENT

E. R. Baumann
Paul E. Morgan
J. L. Cleasby
C. S. Oulman

I. PERMEABILITY OF DIATOMITE FILTER CAKES CONTAINING VARIOUS CLAY MINERALS

P. Regunathan
J. L. Cleasby
E. R. Baumann

II. COATINGS FOR FILTER MEDIA

D. E. Burns
C. S. Oulman
E. R. Baumann

III. DIATOMITE FILTRATION EQUATIONS FOR FLAT AND CYLINDRICAL SEPTA

J. H. Dillingham
J. L. Cleasby
E. R. Baumann

IV. PREDICTION OF DIATOMITE FILTER CAKE RESISTANCE

J. H. Dillingham
J. L. Cleasby
E. R. Baumann

V. OPTIMUM DESIGN AND OPERATION OF DIATOMITE FILTRATION PLANTS

J. H. Dillingham
J. L. Cleasby
E. R. Baumann

VI. USER MANUAL FOR PROGRAM FOR OPTIMIZATION OF PLANT OPERATION

J. H. Dillingham
J. L. Cleasby
E. R. Baumann

SUMMARY STATEMENT
FOR
THIRD PROGRESS REPORT

DESIGN REQUIREMENTS FOR MUNICIPAL DIATOMITE FILTERS

E. Robert Baumann,* Professor of Civil Engineering
Paul E. Morgan,* Professor of Civil Engineering
John L. Cleasby, Professor of Civil Engineering
Charles S. Oulman, Assistant Professor of Civil Engineering

U. S. Public Health Service
Division of Water Supply and Pollution Control
Research Grant WP-00196
Project 549-S

This work was supported by the Iowa Engineering Experiment Station in part through funds made available by Research Grant WP-00196 from the Division of Water Supply and Pollution Control, Public Health Service.

Sanitary Engineering Section
Iowa Engineering Experiment Station
and
Department of Civil Engineering
Ames, Iowa
December 15, 1965

* Principal Investigators

SUMMARY STATEMENT

The research at Iowa State University has been directed along two general objectives. The primary objective has been the development of rational design techniques which will permit engineers to design diatomite and sand filtration plants to operate with maximum economy. The secondary objective has been an investigation of the fundamental mechanism by which particulate matter is removed on a granular filter.

A MATHEMATICAL MODEL has been developed to predict the head loss-time relationship for a diatomite filter under varying operating conditions. The initial equation (FIRST PROGRESS REPORT, PART II; SECOND PROGRESS REPORT, PART II) was found not to be theoretically exact for cylindrical septa because it assumed a constant filtration area, whereas filter area actually increases on cylindrical septa as the filter cake gets thicker. The original equation also neglected the affect of the initial dilution of the incoming water with the clean water in the filter housing resulting from the precoating operation. In many cases the original equation is adequate to predict the head loss-time relationship, especially in short filter runs with low body feed concentrations. However, the error of the original equation can be significant in long filter runs and with high body feed concentrations.

A refined filtration equation has been developed which is suitable for both flat and cylindrical septa and which does include the effect of initial dilution (THIRD PROGRESS REPORT, PART III).

The use of the filtration equations hinges upon the collection of filter cake resistance coefficients and correlation of these coefficients with measureable filtration variables. Early correlation techniques attempted to relate cake resistance (K_4) to the ratio of the concentration of suspended solids in the water to concentration of body feed added to the water (C_S/C_D). A prediction equation of the form $K_4 = a(C_S/C_D)^b$ was found applicable to some waters (SECOND PROGRESS REPORT, PART VI; THIRD PROGRESS REPORT, PART I) such as iron bearing and kaolinite clay bearing waters. The constants "a" and "b" could be evaluated by a few pilot filtration runs.

However, good correlation could not be obtained when filtering lime-softened waters and water containing montmorillonite clay (THIRD PROGRESS REPORT, PARTS I AND IV). It was found that the correlation of filter cake resistance (β index in the new filtration equation) to the filtration variables C_S and C_D could be significantly improved if C_S and C_D were treated as independent variables. The form of the prediction equation used was:

$$\beta = 10^a (C_S/C_D)^b C_D^c$$

The constants a, b, and c are evaluated using a three-dimensional least squares regression approach with the data collected in a series of pilot filtration runs.

As more field data are collected on typical waters, it may be possible to classify a water on the basis of a simple test index such as a silting index* or a refiltration index** and use a β-index prediction equation which is approximately typical for that water based on past experience on similar waters.

---

* Millipore Filter Co.

** Developed by Dr. Victor K. LaMer

The filtration equation and the filter cake resistance prediction equation can be used in conjunction with first cost and operating cost (labor and maintenance) information to optimize plant design. The first attempt to optimize plant design involved making a digital computer comparison of water production cost for one type of water in plants of 3 sizes, using 3 different filtration rates and 6 different terminal head losses (FIRST PROGRESS REPORT, PART III). A more refined computer program (THIRD PROGRESS REPORT, PARTS V AND VI) has been prepared which permits each of the variables to be varied incrementally.

The various components of water production cost are calculated for each specified combination of variables. The 10 combinations resulting in least total cost per unit water production are then output. The capabilities of this program, called "PROGRAM FOR OPTIMIZATION OF PLANT OPERATION" or "POPO", are significantly superior to the program used in the first attempt at cost optimization.

Typical cost data have been collected from manufacturers of filtration equipment and from actual installations. First cost and labor and maintenance cost have been related approximately to filter area. These approximate cost data have been used to "illustrate" the potential of "POPO." Cost information must be input for each use of POPO. Thus, as users of "POPO" obtain better cost data, the new cost data should be used in place of that used in this report to illustrate the program.

Some conclusions have been drawn as a result of using the program and the illustrative cost data (THIRD PROGRESS REPORT, PART V). For example, for waters of good filtrability (low β-index), optimum design occurs at relatively high filtration rates (2 to 3 gpm/sq. ft.) and low terminal head losses. Most applications of diatomite filters have been to waters of good filtrability. Thus, the results of the program support the trend in actual practice toward the use of vacuum filters which have a terminal head loss limited to about 25 ft. and the use of high filtration rates common in many plants. On the other hand, for waters of poor filtrability (high β index), low filtration rates (0.5 to 1 gpm/sq. ft.) and high terminal head losses result in optimum design. Therefore, no fixed filtration rate or terminal head loss should be arbitrarily selected as a uniform design standard for all waters. The recommendation of a filtration rate of 1 gpm/sq. ft., as included in the AWWA Task Group report, when optimization design techniques are not used is thus subject to question.

It is apparent from the progress reported above that development of a sound basis for diatomite filter design is nearly accomplished. Additional time is needed to collect field data on filtration of uncoagulated and coagulated surface waters.

The accomplishments in the area of the second objective have been reported in various Progress Reports (FIRST PROGRESS REPORT, PART IV; SECOND PROGRESS REPORT, PART IV & V; THIRD PROGRESS REPORT, PART II). In brief summary of these studies, it can be reported that diatomite particles can be permanently coated with either metal coagulant ions (iron or aluminum) or with organic polyelectrolytes. The applied coatings may alter or even reverse the zeta potential of the diatomite particles. The applied coatings may either increase or slightly decrease the filter cake resistance depending on the type of coating applied and other water characteristics.

The application of coatings to diatomite filter aids to reduce or reverse their zeta potential so they become electropositive may enhance removal of colloidal sized impurities by mutual coagulation or other mechanisms. Some preliminary filtration results have been obtained to support this expected result. However, much work remains to be done to demonstrate the value of applied coatings to filtration effectiveness and to determine the mechanisms responsible. Results of this study have potential importance in sand filtration as well as diatomite filtration.

PART I

PERMEABILITY OF DIATOMITE FILTER CAKES CONTAINING VARIOUS CLAY MINERALS

P. Regunathan
J. L. Cleasby
E. R. Baumann

Progress Report

PERMEABILITY OF DIATOMITE FILTER CAKES CONTAINING VARIOUS CLAY MINERALS

by

Perialwar Regunathan
John L. Cleasby
E. Robert Baumann

United States Public Health Service
Division of Water Supply and Pollution Control
Research Grant WP-00196

Project 549-S

Municipal Diatomite Filters

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PERMEABILITY OF DIATOMITE FILTER CAKES CONTAINING VARIOUS CLAY MINERALS

by

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LIST OF ABBREVIATIONS

Abbreviation	Meaning
fps	feet per second
ft	feet
gal	gallons
gm	grams
gpm	gallons per minute
in.	inches
l	liters
lb	pounds
mg	milligrams
mg/l	milligrams per liter
min	minutes
no.	number
ppm	parts per million parts by weight
sec	seconds
sq	square
turb.	turbidity
^{o}F	degrees Fahrenheit

INTRODUCTION

PURPOSE AND SCOPE OF THIS STUDY

Extensive studies have been conducted in the field of diatomite filtration to find out the filtering characteristics of body feed layers containing various grades of diatomite and iron floc from various sources [9,10]. Many surface waters contain clay minerals in suspension together with other types of impurities. Therefore, it would be desirable to have a knowledge of the effect of different clay minerals on the permeability of the body feed layer to design a diatomite filtration plant for the filtration of surface waters.

The purpose of this study was to determine the permeability (represented by an impermeability coefficient) of the body feed layer for different grades of diatomite containing various clay minerals. The specific objectives are:

1. To determine if acceptable effluent quality can be obtained from a pilot pressure filter plant filtering University tap water to which a clay suspension has been added.
2. To determine the permeability of the body feed layers obtained using different grades and amounts of diatomite containing various amounts of different clay minerals.

LITERATURE REVIEW

The applicability and limitations of diatomite filtration for municipal water supplies have been studied[15]. A reservoir water in which the suspended solids content was mainly due to dead algae was used. For average water quality conditions the total cost per unit volume of water treated was found to be the same for diatomite filtration without pretreatment and conventional filtration with pretreatment. Diatomite filtration had a decided advantage over conventional filtration where space was limited and pumping was necessary.

The results of all the important research which had been done on diatomite filtration of water up to 1957 have been gathered together, analyzed and summarized[14]. This is a concise report of the work done to that time.

Later on a number of runs using three different types of filters including a pilot pressure filter tap water containing either 2, 4, or 8 ppm of iron in the form of hydrous ferric oxide was filtered at three different rates, 1, 2, and 3 gpm per sq ft[11]. The data collected were used in developing a theory of filtration and in determining the optimum conditions of filtration[4]. It was concluded that three different body feed rates may be considered as optimum rates. Optimum body feed rates identified were those which will give maximum run length, minimum diatomite usage or minimum overall production cost per unit volume of water treated. For minimum production cost, a flow rate of 1.0 gpm per sq ft, high terminal head loss, and a body feed rate just sufficient to produce a linear head loss curve were found to be the optimum provisions.

Next an equation was developed for head loss development in diatomite filtration based on Darcy's law[4].

$$H = K_3QW_1 + K_4C_DQ^2t \times 8.33 \times 10^{-6} \ldots \quad (1)$$

where: H = total head loss across the filter cake in ft of water and K_3, K_4 = constants for a given filter media including the coefficient of permeability of filter cake and the bulk density of material in the precoat layer and the body feed layer respectively in $\frac{(\text{min})\ (\text{ft})^5}{(\text{lb})\ (\text{gal})}$

Q = filtration rate in gpm per sq ft

W_1 = weight of precoat diatomite in lb per sq ft

C_D = concentration of body feed in ppm

t = time of filtration in min

The development of this equation is given briefly here. Since the flow through a filter is well established to be in the laminar range and obeys Darcy's law, then

$$Q = K_pH/L \text{ or } H = QL/K_p = KQL \quad (2)$$

where: Q = rate of flow in gpm per sq ft

K_p = coefficient of permeability in gpm per sq ft

H = head loss in ft of water

L = thickness of filtering layer in ft

$K = 1/K_p$

Now it is assumed that the head loss developed across the filter consists of two independent parts: the head loss through the precoat and the head loss through the body feed layer. The subscript 1 will refer to the precoat terms and subscript 2 will refer to the body feed terms.

$$H = K_1QL_1 + K_2QL_2 \tag{3}$$

The thickness of the filter cake can be determined with a knowledge of the material in the layer and the in-place bulk density of the material.

$$L_1 = W_1/d_D \tag{4}$$

$$L_2 = (W_S + W_D)/d_s \tag{5}$$

where: W_1 = weight of precoat diatomite in lb per sq ft

d_D = in-place bulk density of the diatomite in the layer in lb per ft^3

W_S = weight of suspended solids in lb per sq ft

W_D = weight of body feed diatomite in lb per sq ft

d_s = in-place bulk density of body feed layer in lb per ft^3

For the purpose of simplifying the equation, an assumption is made that the effect of the suspended solids on the filter cake thickness is negligible.

$$\text{ie. } L_2 = W_D/d_D \tag{6}$$

Therefore:

$$H = K_1QW_1/d_D + K_2QW_D/d_D \tag{7}$$

$$= K_3QW_1 + K_4QW_D$$

where: $K_3 = K_1/d_D$ and $K_4 = K_2/d_D$

$$\text{But, } W_D = C_DQt \times 8.33 \times 10^{-6} \tag{8}$$

where: C_D = concentration of body feed used in ppm. 8.33×10^{-6} is the necessary conversion factor

Therefore: $H = K_3QW_1 + K_4C_DQ^2t \times 8.33 \times 10^{-6}$.....1

An exponential relationship exists between K_4 and the ratio of suspended solids concentration to body feed concentration; thus, a log-log plot of K_4 and the corresponding ratios should form a straight line.

The same equation has been presented in a slightly modified form[7]. The simplifying assumption, (Equation 6), made to neglect the effect of suspended solids on cake thickness was omitted. This is a more complete equation for K_4 (Equation 11).

$$L_2 = \frac{W_2}{d_s} = \frac{W_s + W_D}{d_s}$$

$$W_2 = (C_D + C_S)\,Qt \times 8.33\times10^{-6} \tag{9}$$

Therefore:

$$H = K_1Q\frac{W_1}{d_D} + \frac{K_2}{d_s}\,Q^2(C_D + C_S)t \times 8.33 \times 10^{-6} \tag{10}$$

$$= K_3QW_1 + K_4Q^2C_Dt \times 8.33 \times 10^{-6}$$

$$\text{where } K_4 = \frac{K_2}{d_s}\;\frac{(C_D+C_S)}{C_D} \tag{11}$$

Recently, the permeability of filter cakes containing suspended solids which were obtained by the addition of different chemical compounds to water were studied[10]. Five chemicals were used, ferrous sulphate, ferrous chloride, ferric chloride, ferric sulphate, and aluminum sulphate. Impermeability values (K_4) obtained with raw water containing flocculent solids from trivalent iron salts and aluminum salt were approximately ten times as great as those obtained when the suspended solids were derived from the bivalent salts. Microscopic examination of the solids showed that the particle size of floc from the trivalent iron salts was considerably larger than that from the bivalent salts and was about the size of the filter media particles themselves. The effect of adding the body feed at two different places (to the raw water tank and to the influent line) on K_4 values was studied and no difference in K_4 values regardless of the body feed technique was found.

In a similar study several runs were made to determine the permeability of the body feed layer for different grades of diatomite using water containing hydrous ferric oxide floc[9]. Ferrous sulphate was used as the source of iron floc. Another purpose of this study was to correlate the impermeability of the body feed layer (K_4) with the impermeability of the clean diatomite (K_3). Finer grades of diatomite gave higher K_4 values in the filtration of a flocculent solids. Also, the percent change in K_4 value was not as great as the corresponding percent change in K_3 value.

A modified form of the diatomite filtration equation in which K_3 and K_4 of the original equation have been replaced by α_1, α_2, μ, g and d has been published[5]. The terms K_3 and K_4 are not truly constants for a given filter media and suspended solids but vary with temperature as the viscosity and density of the liquid being filtered change. But α_1 and α_2 are not temperature dependent; they are constants for a given filter media and suspended solids. The modified equation is the following:

$$H = 6.26 \times 10^{-9} \frac{\mu Q}{gd} (\alpha_1 W_1 + \alpha_2 C_D Qtd \times 10^{-6}) \quad (12)$$

where: α = the average specific resistance of the portion of the filter cake through which a pressure drop exists ($ft^2/lb\ sec^2$)

μ = absolute viscosity of filtrate (centipoise)

d = bulk density of water (lb/gal)

g = gravitational constant (ft/sec^2)

$$\alpha_1 = \frac{K_3 gd}{6.26 \times 10^{-9} \mu} \quad (13)$$

$$\alpha_2 = \frac{K_4 gd}{6.26 \times 10^{-9} \mu} \quad (14)$$

LABORATORY APPARATUS AND PROCEDURE

Two clays were used to produce artificial turbid waters in this study. A pilot diatomite filter was used in a number of runs to remove the clays from the water at a flow rate of 1.0 gpm per sq ft. In the runs, various grades and rates of body feed diatomite were used. The data from the runs were used to calculate the impermeability values (K_4) for the resulting filter cakes.

RAW WATER

The turbid raw water used in all tests was prepared by adding tap water and a clay slurry continuously to a mix tank. The tank had a capacity of 252 gallons. The mixing was done mechanically by a paddle with a peripheral velocity of 2.4 fps. Tap water was added to the tank continuously at a constant rate by using a flow control valve.*

The clay slurry was fed into the mix tank by a slurry feeder. † The slurry was prepared in the feeder by mixing a known amount of clay in distilled water and leaving it overnight, air agitated for fifteen to twenty-one hours. A pump, attached to the feeder, flushed the slurry in small equal quantities into the mix tank. The turbidity of the raw water could be varied by changing the concentration of slurry or by adjusting the length of stroke of the metering diaphragm in the feeder. The turbidity of water used in different experiments of this study varied from 30 to 150 units.

The tap water for the University is obtained from deep wells. This water has been treated for iron removal by aeration, sedimentation, and rapid sand filtration. A typical mineral analysis is the following[13]:

Total residue	532 mg/l
Alkalinity (as $CaCO_3$)	320 mg/l
Aluminum	0.05 mg/l
Calcium	114 mg/l
Chloride	11.0 mg/l
Copper	0.25 mg/l
Fluoride	0.40 mg/l
Iron	0.05 mg/l
Magnesium	61.0 mg/l
Manganese	0.20 mg/l
Nitrate	0.70 mg/l
Phosphate	0.15 mg/l
Potassium	2.50 mg/l
Silica	12.0 mg/l
Sodium	19.5 mg/l
Sulphate	210.0 mg/l

The temperature of the water in the mix tank was controlled by using a thermostat ‡ which actuated a relay and in turn a solenoid valve on the hot water feed line. The mixing of hot and cold water took place before flowing through the regulator. The temperature of raw water maintained in this study was 60°F.

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*Standard Flow Control 76, Dole Valve Company, Morton Grove, Illinois.

†Series A-710 Slurry Feeder, Wallace and Tiernan, Inc., Belleville, New Jersey.

‡Thermoswitch-thermostat, Fenwal Inc., Ashland, Massachusetts.

PILOT PLANT

The pilot plant used in this study had been constructed and operated in previous experiments[10, 12]. No major changes were made in the pilot plant for this study (figs. 1 and 2).

The raw water prepared in the mix tank entered a small hopper through a float valve. The body feed diatomite was added to the water flowing through the hopper. The water was pumped from the hopper through the filters, and thereafter through a flow meter and a flow regulator. The rate of flow through the filters was controlled at a constant rate by the flow regulator // and it was measured by the rotameter #. The head loss across the filter cake was measured by a mercury manometer. Turbidity of the raw water and filtrate was measured continuously by two turbidimeters.

The body feeder used in this study was a volumetric feeder with two feed screws.** A time clock controlled the feeder to run for a predetermined portion of each minute. By using the right screw and setting, the body feed rate could be varied from nearly 50 to around 2000 mg/l at the flow rate of 1.0 gpm per sq ft used in this study.

The filter housing contained two septums which consisted of a sock, made from a synthetic fabric, stretched over a plastic frame.

The septums, 3 1/2 inches in diameter and 14 inches in length, provided a total filtering area of 2.136 sq ft.

One of the two recirculation lines in the pilot plant connected the effluent side of the filter housing through the main pump to the inlet side of the housing. This was used during the precoating operation only. The other recirculation line connected the inlet side of the housing through a recirculation pump back to the inlet side itself. This recirculation was used throughout the run to provide an upward velocity in the housing to facilitate even cake formation throughout the filtering area.

For the precoating operation, clean water was drawn from a 32 gallon tank. The level of the University tap water in the tank was maintained by a float valve.

//Kates type SA, W. A. Kates Company, Deerfield, Illinois.

# Flow rator Meter, Figure 1735 Standard Enclosed Meter, Fisher and Porter Company, Hatboro, Pennsylvania.

**BIF Model 25-01, BIF Industries, Division of New York Air Brake Company, Providence, Rhode Island.

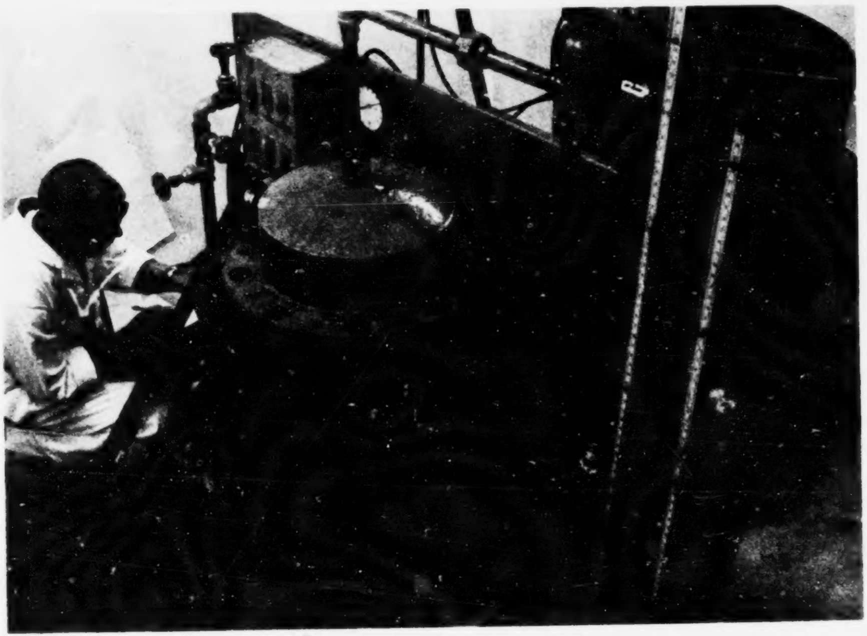

Fig. 1. Pilot pressure diatomite filter plant.

METERING EQUIPMENT

To measure the turbidity of the influent and effluent continuously, two photoelectric turbidimeters and an automatic recorder were used throughout the study except for a few trial runs in the beginning. A high-range turbidimeter## for measuring the influent turbidity and a low-range one ## for measuring the effluent turbidity were used, and the readings from both were continuously recorded on a multipoint recorder. Each turbidimeter was calibrated against the Jackson Candle Turbidimeter for each clay used (1).

C.R. high-range turbidimeter and C.R. low range turbidimeter, Hach Chemical Co., Ames, Iowa.

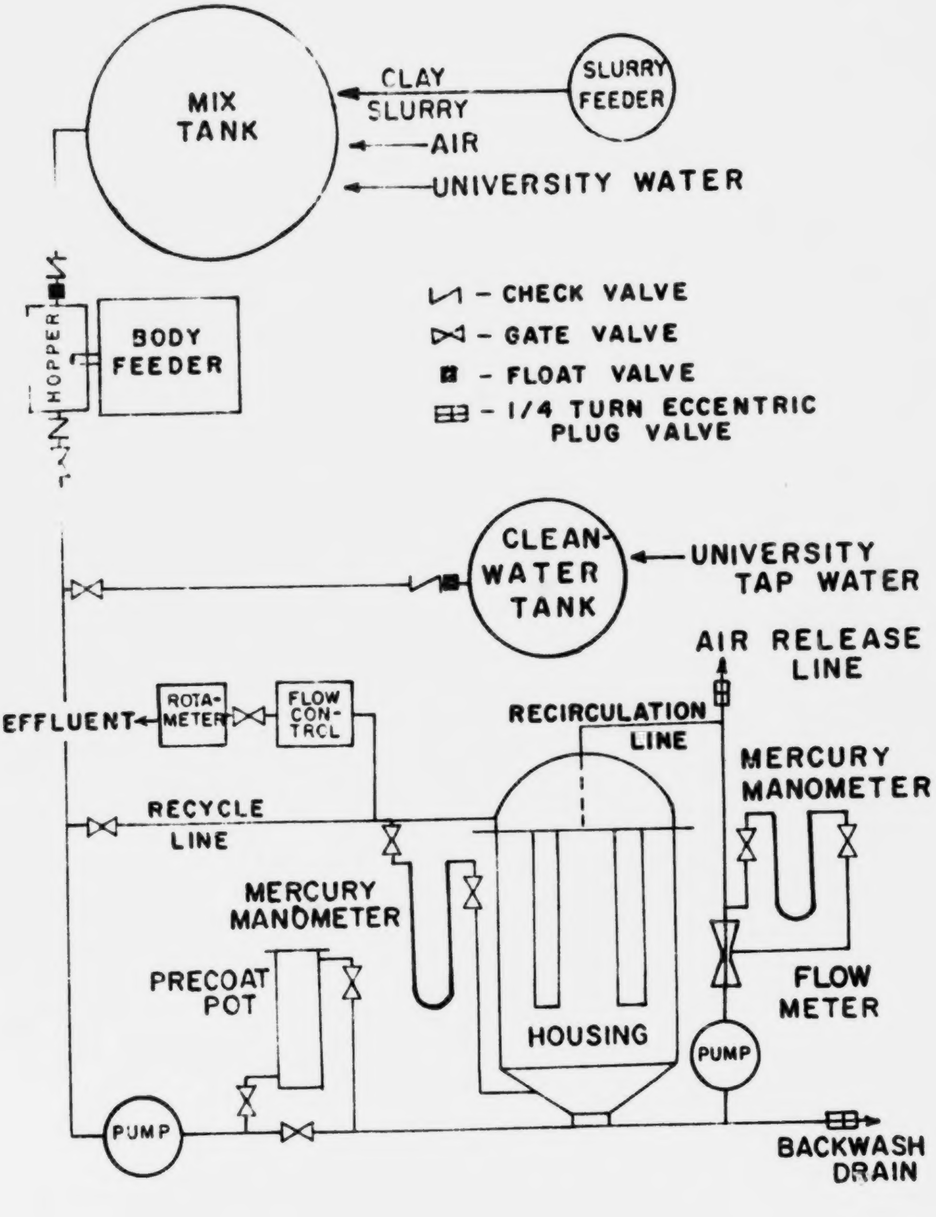

Fig. 2. Pilot pressure diatomite filter plant.

High-range turbidimeter* (Fig. 3)

The high-range turbidimeter is a 6-in. metal tube, approximately 46-in. long. The water enters the tube about 1 1/2 ft from the bottom and leaves through two pipe connections provided, one at the bottom and one eleven inches from the top. A light scource, two lenses, and a number of photoelectric cells are fixed above the water surface. The cells are mounted around the lenses on the bottom side, and the light from the source above cannot reach the cells directly. The light source and the lenses send a beam of light downward into the water; the light is reflected by the suspended solids at and near the surface of the water. This reflected light is picked up by the cells; this results in the generation of a small electric potential which is measured and recorded by the automatic recorder. The interior of the tube of the turbidimeter is painted dull black to prevent any possible reflection from the sides and bottom of the tube. The electric potential developed is thus a function of the amount of suspended solids in the water.

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* C.R. high-range turbidimeter and C.R. low-range turbidimeter, Hach Chemical Co., Ames, Iowa.

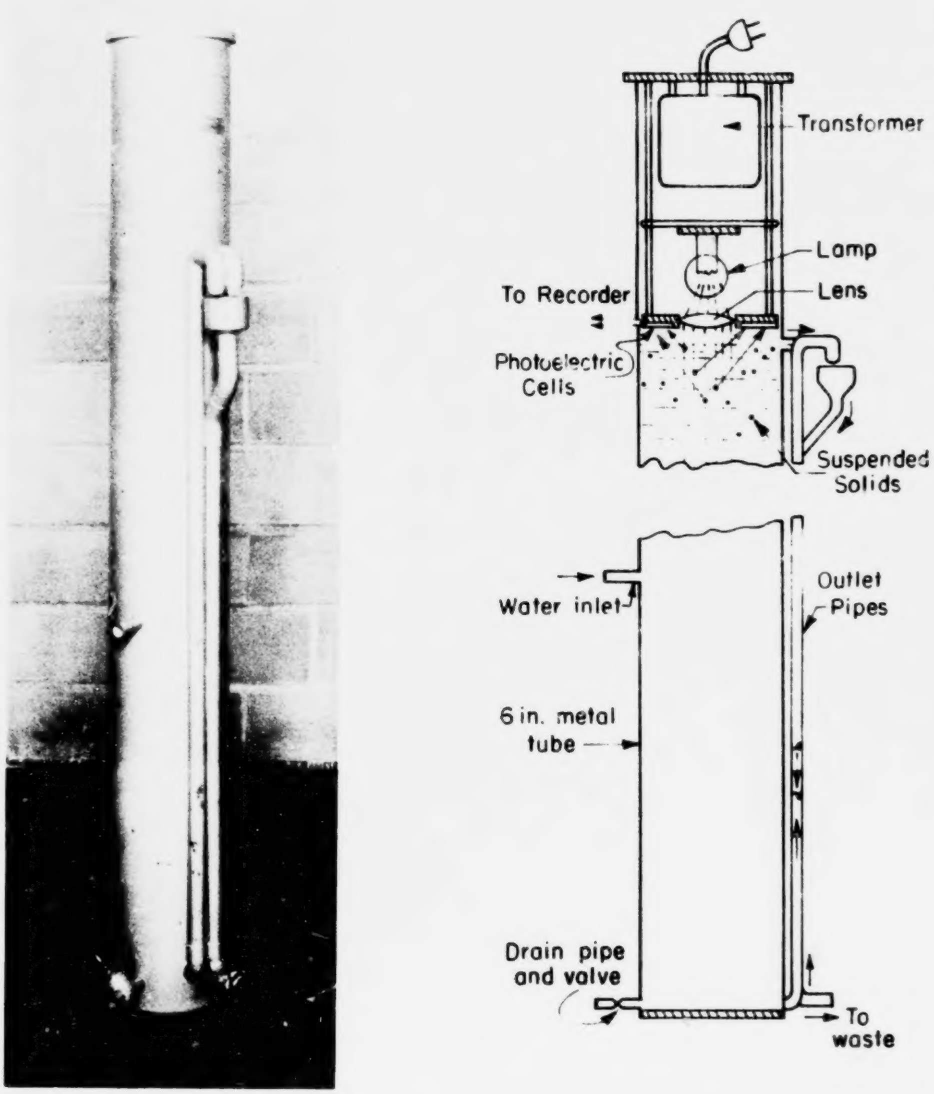


Fig. 3.
High-range turbidimeter

Low-range turbidimeter (Fig. 4)

The low-range turbidimeter, though in many ways similar to the high-range turbidimeter, has some significant differences. This turbidimeter is a 4-in. plastic tube, approximately fifty inches long. The water enters at the bottom and overflows at about 1 ft from the top. The photoelectric cells are mounted around the circumference at about the middle of the tube. When the beam from the light source and the lenses passes through the water column, the light is scattered by the particles in the water and this scattered light is picked up by the cells. This results, as in the high-range turbidimeter, in the production of a small potential which is measured by the recorder. The merits and details of the turbidimeter have been described elsewhere[6].

Recorder[≁] and helipot [≠] (Fig. 5)

A multipoint, self-balancing potentiometer-recorder recorded continuously the output of the photoelectric cells of the turbidimeters. The recorder has a full scale reading of 5 millivolts. Two variable resistors, helipots, are connected in parallel with the recorder (Fig. 6). These sliding wire helipots have dials indicating the slide wire position. The dials can be set to obtain any desired scale reading in the recorder for a given output of the turbidimeter.

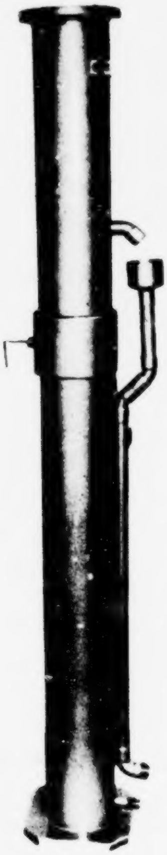
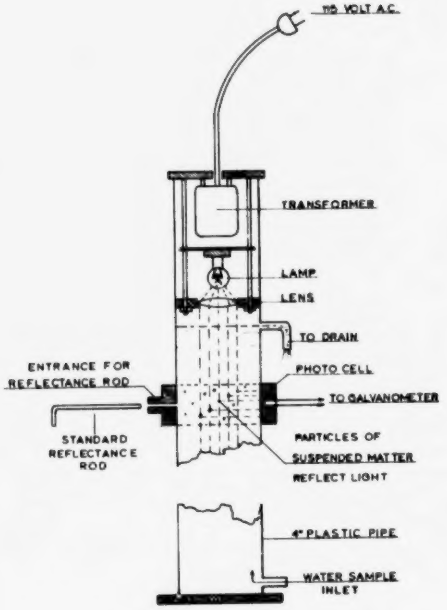


Fig. 4.
Low-range
turbidimeter.



[≁] Type 153 Universal Electronic Multipoint Recorder, Minneapolis-Honeywell Regulator Co., Philadelphia, Pennsylvania.

[≠] Helipot, Beckman Instruments, Inc., Fullerton, California.

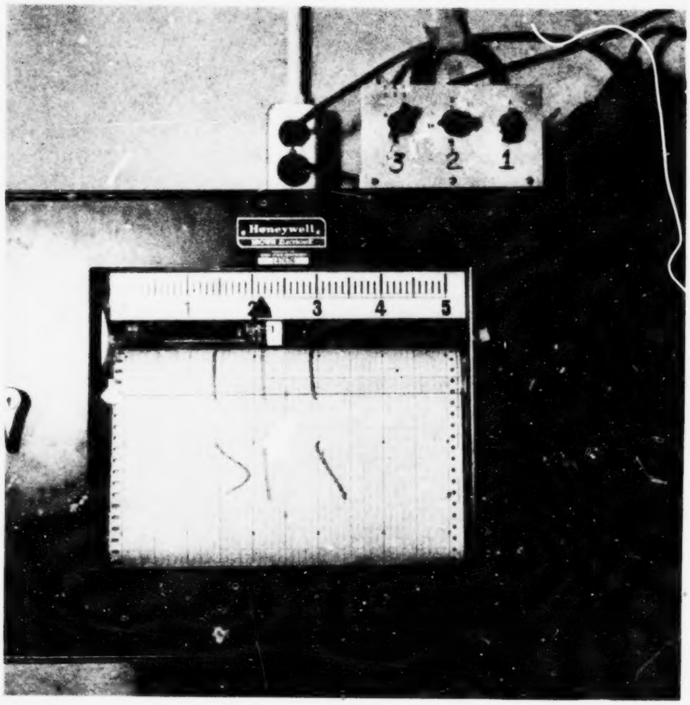
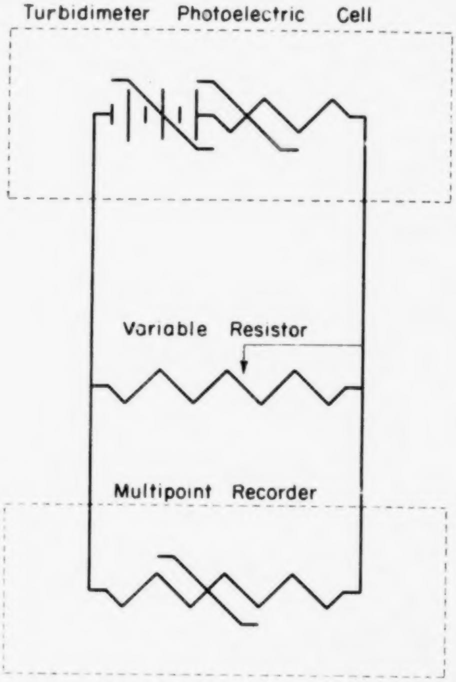


Fig. 5. Multipoint recorder.

Calibrations

The Jackson Candle Turbidimeter is the standard instrument for measuring turbidity of suspensions [1]. Any other instrument used should be calibrated against the Jackson Candle Turbidimeter using the same type of suspended solids to be subsequently measured. Accordingly, each turbidimeter was calibrated for each clay mineral with several suspensions of different turbidity levels. Suspensions for calibrations were prepared by diluting a clay slurry with distilled water to achieve the desired turbidity level. A small centrifugal pump and a bucket were used to circulate the prepared suspension through the turbidimeter for the calibration work. In each calibration, water with the highest turbidity desired was used first, and the dial in the variable resister was adjusted to get a desired reading, nearly 5 millivolts. This setting of the resistor was locked in position and was not changed during the rest of the calibration work and during the runs using that clay as the suspended solids source. A constant rate of circulation through the turbidimeter was controlled during the calibration work so that there was neither any settling of particles in the bucket

Fig. 6. Circuit connection of the recorder and the turbidimeter.



nor a submerged flow at the outlet of the turbidimeter. The same flow rate was maintained in the subsequent use of the instrument.

In calibrating the high-range turbidimeter, three separate samples were collected for each clay suspension from the outlet of the turbidimeter. The turbidity of these samples was measured with the Jackson Candle Turbidimeter. The average of all the three measurements was used as the turbidity of the suspension. A plot of these turbidity values versus recorder reading was used during the subsequent experiments.

The low-range turbidimeter was calibrated by preparing a standard suspension with a turbidity higher than 25 units. The turbidity was measured with a Jackson Candle Turbidimeter. This standard suspension was then diluted with distilled water in various proportions to obtain suspensions having different desired turbidities. These suspensions were then circulated through the turbidimeter, and the readings in the recorder for a selected setting of the variable resistor were noted. At the end of each calibration, distilled water was circulated through the turbidimeter, and this reading of the recorder also was noted. A plot of turbidity values versus the reading of the recorder was used during the subsequent experiments.

OPERATING PROCEDURE

First, the clay slurry feeder was started, and the tap water valve was opened so that the raw water would be available when the filtering cycle was started. The precoating operation was started by pumping tap water from the clean water tank into the system. After getting the air out of the system, the recirculation pump was started, and both of the recirculation lines were opened. Then, the precoat diatomite was weighed and placed in the precoat pot. A precoat diatomite of 0.15 lb per sq ft was used in all the runs conducted for this study. The precoat pot was filled with water and pressurized. The precoat slurry was then recycled through the pot and the filter until the precoat was formed on the septums and the water in the housing became clear.

The following procedure was used in starting the filtering operation: the filter effluent valve was first opened; the filter influent valve from the hopper was opened; the body feeder was started; the valve in the line from clean water tank was closed; the filtration rate was set by adjusting the rate controller. A rate of 1.0 gpm per sq ft was used in all the runs. The following data were noted periodically during a run:

1. Clock time
2. Temperature of raw water
3. Influent turbidity
4. Effluent turbidity
5. Head loss in inches of mercury

A plot of head loss in ft of water versus filtrate volume in gal per sq ft was prepared while a run was proceeding. When the linearity or non-linearity of the head loss curve was definitely established, the run was terminated. Usually, the head loss at this time ranged from 20 to 100 ft of water. The filter was then cleaned by an air-gurgle type backwash. Before starting the next run, the whole system was cleaned twice by pumping the system full of clean water and draining it down.

The diatomite in the body feeder was changed after every six to eight hours of operation, so as to avoid degradation of diatomite in the feeder. The body feed rate was measured by collecting and weighing two ten-minute samples before and after each run.

SUMMARY OF RUNS

Two clays and two grades of diatomite were used in this study. The experiments were divided into five series (Table I). The run number, the clay, the grade and the lot number of diatomite used for conducting each series are presented in the table.

All runs were conducted between January 2, 1964 and August 8, 1964 and are reported in chronological order (Table II). Factors such as the influent turbidity, effluent turbidity, suspended solids concentration, body feed concentration and impermeability values are shown for each series and run number. When the effluent turbidity was less than that of distilled water, it has been reported as 0.00 units.

Several trial runs were made to become familiar with the equipment and the procedure to be used during a run. During these runs, a leak was noticed in the recirculation pipe; this was remedied before the other series of runs were conducted. Runs conducted before the recirculation pipe started leaking are grouped in series A. These are reported only as trial runs, because the turbidimeters were not used, and the turbidity measurements were not reliable.

TABLE I. GROUPING OF RUNS

Series	Run number	Clay mineral	Grade of diatomite	Lot no.
A	1 through 4	Ball clay*	Celite 545 †	1
	5	Ball clay	Hyflo Super-Cel†	1
B	1 through 15	Ball clay	Celite 545	1
	16 through 18	Ball clay	Celite 545	2
C	1 through 15	Ball clay	Hyflo Super-Cel	1
D	1 through 9	Wyoming bentonite ≠	Hyflo Super-Cel	1
	10 through 16	Wyoming bentonite	Hyflo Super-Cel	2
E	1 through 2	Wyoming bentonite	Celite 545	2

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* Old Hickory No. 5 ball clay, Old Hickory Clay Co., Paducah, Kentucky.

† Filter aids, Johns-Manville Corporation, New York, N.Y.

≠ Black Hills Bentonite, International Mineral and Chemical Corporation, Skokie, Illinois.

TABLE II. SUMMARY OF RUNS

Series and Run No.	Suspended Solids		Average Effluent Turb. Units	Body Feed Concentration (mg/l) (C_D)	$\frac{T}{C_D}$	$\frac{C_S}{C_D}$	K_4	$[K_4]$*	α_2
	Influent Turb. Units (T)	Concentration (by weight) mg/l (C_S)			$\frac{\text{units}}{\text{mg/l}}$	$\frac{\text{mg/l}}{\text{mg/l}}$	$\frac{\text{min ft}^5}{\text{lb gal}}$	$\frac{\text{min ft}^5}{\text{lb gal}}$	$\frac{\text{ft}^2}{\text{lb sec}^2}$
A 1	29	--	--	88	0.33	--	47	--	--
2	35	--	0.2	21.4	1.63	--	700	--	--
3	32	--	0.2	102	0.31	--	35.4	--	--
4	21	--	0.2	62.7	0.34	--	70.2	--	--
5	21	--	trace	28.1	0.75	--	500	--	--
B 1	34.5	33	3.0	0	--	--	--⌿	--	--
2	42.0	37	0.03	53.8	0.781	0.687	118.0	70.0	4.5×10^{12}
3	37.0	34	0.08	110.0	0.336	0.309	2[illegible].3	15.5	7.74×10^{11}
4	37.0	34	0.00	211.0	0.175	0.161	5.87⌿	5.06	2.24×10^{11}
5≠	62.0	49.5	0.03	68.8	0.90	0.72	--⌿	--	--
6≠	81.0	61.0	0.17	66.6	1.215	0.915	--⌿	--	--
7	136.0	98.5	1.0	85.0	1.60	1.16	--⌿	--	--
8	108.0	79.0	0.05	132.7	0.815	0.595	132.5	83.1	5.05×10^{12}
9	115.0	83.5	0.15	125.5	0.916	0.665	152.0	91.4	5.79×10^{12}
10	115.0	83.5	0.20	92.0	1.25	0.91	--⌿	--	--
11	105.5	77.0	0.10	101.0	1.045	0.761	--⌿	--	--
12	108.5	79.0	0.18	131.4	0.825	0.60	110.5	69.0	4.21×10^{12}
13	106.0	77.5	0.10	131.0	0.806	0.591	117.0	73.5	4.45×10^{12}
14	108.0	79.0	0.05	131.8	0.820	0.599	130.5	81.5	4.97×10^{12}
15	119.0	86.5	0.08	213.0	0.559	0.406	44.2	31.4	1.68×10^{12}
16	128.0	93.0	1.30	155.5	0.823	0.598	113.0	70.6	4.30×10^{12}
17	64.0	50.5	0.90	76.3	0.839	0.661	124.5	75.0	4.74×10^{12}
18	100.0	73.0	1.75	125.5	0.796	0.581	98.5	62.3	3.75×10^{12}
C 1	80.5	61.0	0.08	0	--	--	--⌿	--	--
2	127.0	92.5	0.00	73.5	1.73	1.26	--⌿	--	--
3	121.5	88.5	0.00	106.6	1.14	0.835	--⌿	--	--
4	68.0	53	0.02	73.7	0.92	0.719	529.0	307	2.015×10^{13}
5	90.0	67	0.00	90.1	1.00	0.744	645.0	370	2.46×10^{13}
6	88.0	65.5	0.01	74.8	1.17	0.875	--⌿	--	--
7	70.0	54.5	0.00	50.1	1.40	1.09	--⌿	--	--
8 //									
9	101.5	74.0	0.00	62.3	1.63	1.19	--⌿	--	--
10	104.0	76.0	0.00	85.8	1.20	0.885	--⌿	--	--
11	92.0	68	0.00	94.4	0.975	0.721	594	345	2.26×10^{13}
12	86.0	64.0	0.00	58.7	1.46	1.09	--⌿	--	--
13	87.0	65.0	0.00	49.8	1.75	1.30	--⌿	--	--
14	87.5	65.0	0.00	105.0	0.83	0.619	360	222	1.37×10^{13}
15	92.0	68.0	0.00	149.3	0.62	0.455	185	127.5	7.05×10^{12}
D 1	88.0	139.0	0.00	120.5	0.73	1.15	--⌿	--	--
2	89.0	141.0	0.00	150.0	0.59	0.94	--⌿	--	--
3	96.5	152.0	0.00	191.0	0.505	0.796	--⌿	--	--
4	78.5	125	0.00	599	0.131	0.209	294	243	1.12×10^{13}
5 //									
6	91.0	144	0.00	495	0.182	0.291	479	371	1.82×10^{13}
7	91.0	144	0.00	410	0.222	0.351	893	661	3.40×10^{13}
8	83.0	147	0.00	220	0.422	0.668	--⌿	--	--
9	85.0	135	0.00	1033	0.082	0.1305	58.8	52.0	2.24×10^{12}
10	45.0	72.0	0.00	335.5	0.134	0.214	438.0	360	1.67×10^{13}
11	123.0	193.0	0.00	806	0.153	0.249	233	194	8.88×10^{12}
12	45.5	72.5	0.00	347	0.131	0.209	485.0	400	1.85×10^{13}
13 //									
14	45.5	72.5	0.00	365	0.125	0.199	374	312	1.42×10^{13}
15	85.0	134	0.00	670	0.127	0.200	202	168	7.70×10^{12}
16	32.5	53	0.00	253.5	0.128	0.209	652	540	2.48×10^{13}
E 1	94.0	148.5	26.00	177	0.53	0.84	--⌿	--	--
2	92.5	146	25.00	303.5	0.305	0.48	--⌿	--	--

---

* Discussion on $[K_4]$ values will be presented later in chapter 6.

⌿ Indeterminate due to non-linear head loss curve.

≠ Body feed degradation is possible.

//Not completed due to unforseen developments.

TEST RESULTS

BALL CLAY

Runs in series B and in series C were conducted using water containing ball clay // as a source of suspended solids. Celite 545 was used as the filter media in series B and Hyflo Super-Cel was used in series C.

Series B

Eighteen runs were conducted in this series using different ratios of turbidity to body feed concentration. Runs numbered 8 and 12 through 14 were conducted to determine the reproducibility of the results using this grade of diatomite. The head loss was observed during these four runs (Fig. 7). The turbidity of the raw water averaged 108 units, and the body feed rate averaged 131.5 ppm. K_4 values of the cakes ranged from 110.5 to 132.5. The reproducibility was considered satisfactory.

The head loss curves in Fig. 7 and in the figures following show a curved portion in the beginning and then a straight line or an extension of the curve itself depending upon the body feed concentration used. This curved portion in the beginning was the result of low head loss increase which lasted for the initial 30 gal/sq ft of filtrate. This behavior can be accounted for by the clear water used for precoating operation taking nearly 30 minutes to leave the system at a flow rate of 1.0 gpm/sq ft.

// Old Hickory No. 5 Ball clay, Old Hickory Clay Co., Paducah, Kentucky.

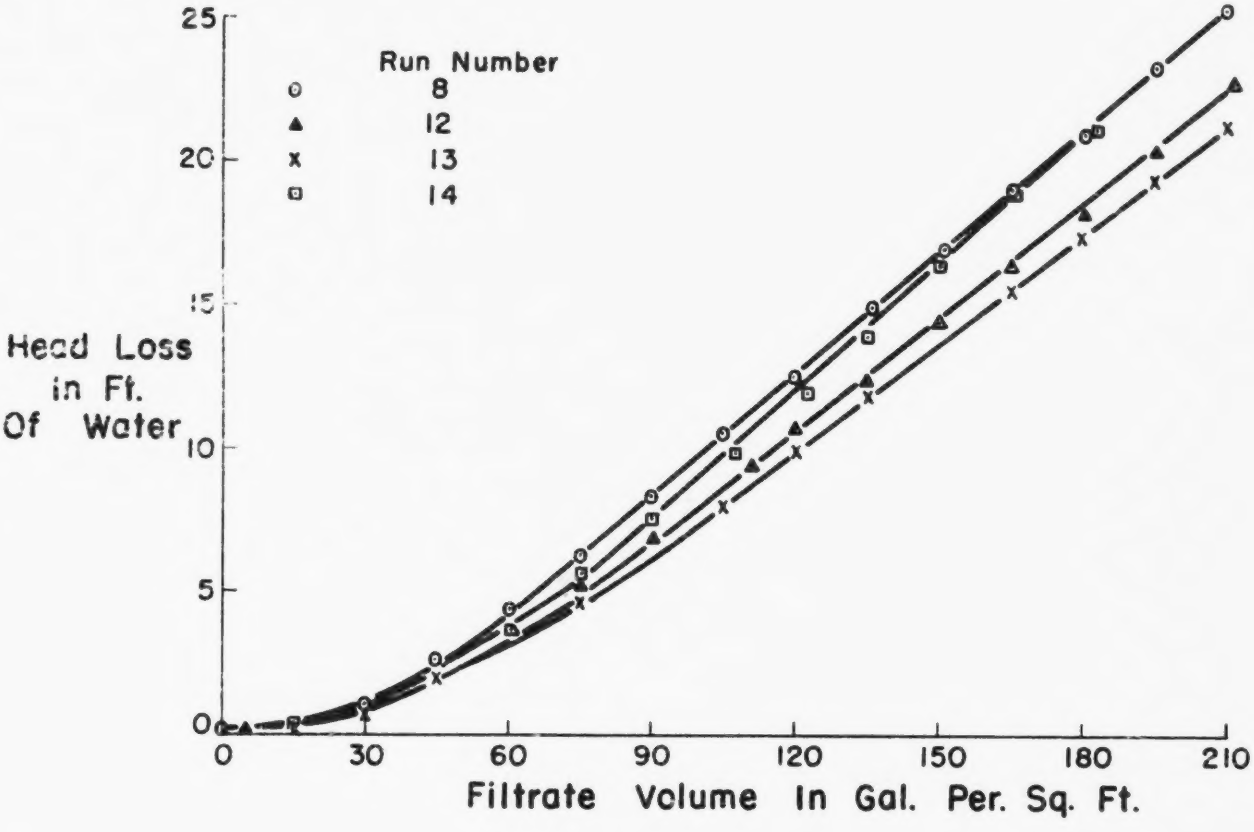


Fig. 7. Reproducibility of head loss curve for Series B.

The last three runs of this series were conducted with diatomite from a shipment different from that used for the first fifteen runs. The turbidity of the effluent during the first fifteen runs was low; during the last three runs about 2 percent of the solids in the influent was found to be passing through the filters. Impermeability values (K3) of different manufactured lots of diatomite are likely to be different from each other[7]. K_3 values determined for these two lots of the same grade were 0.76 and 0.62 respectively. The passing of clay through the filters during the last three runs could be because the diatomite used was comparatively (20%) more permeable than the diatomite used for the previous runs.

Data were collected in runs 3, 9, 10 and 15 (Fig. 8). Ratios of turbidity to body feed concentration of these runs were 0.34, 0.92, 1.25 and 0.56 respectively. The head loss curve for run 10 was parabolic and so was not used for K_4 determination.

A log-log plot of all the K_4 values and the corresponding ratios of turbidity to body feed concentration showed a straight line relationship (Fig. 9).

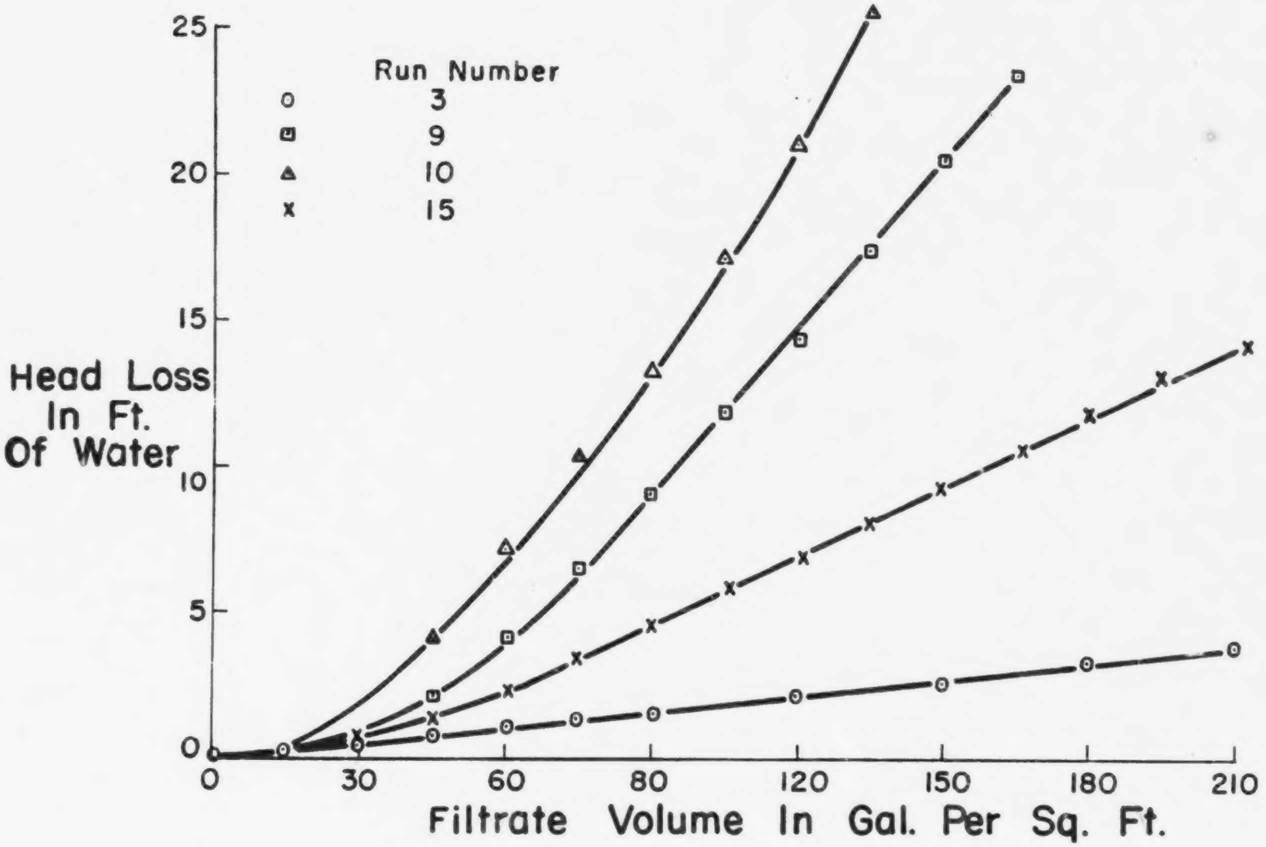


Fig. 8. Variation of head loss for different body feed rates and turbidity levels in Series B.

Series C

This series of runs was conducted with Hyflo Super-Cel as the filter media and water containing ball clay as the suspended solids. The reproducibility of the results was demonstrated in runs 5 and 11 (Fig. 10). The turbidity of the water used in these two runs averaged 91 units, and the body feed rate was 92 ppm. Head loss data were obtained in runs 12, 14, and 15 (Fig. 11). Turbidity to body feed concentration ratios during these three runs were 1.46, 0.83 and 0.62 respectively. The head loss curve for run 12 was parabolic and was not used for K_4 determination.

K4 values were obtained in all runs in this series and the corresponding ratios of turbidity to body feed concentration were determined

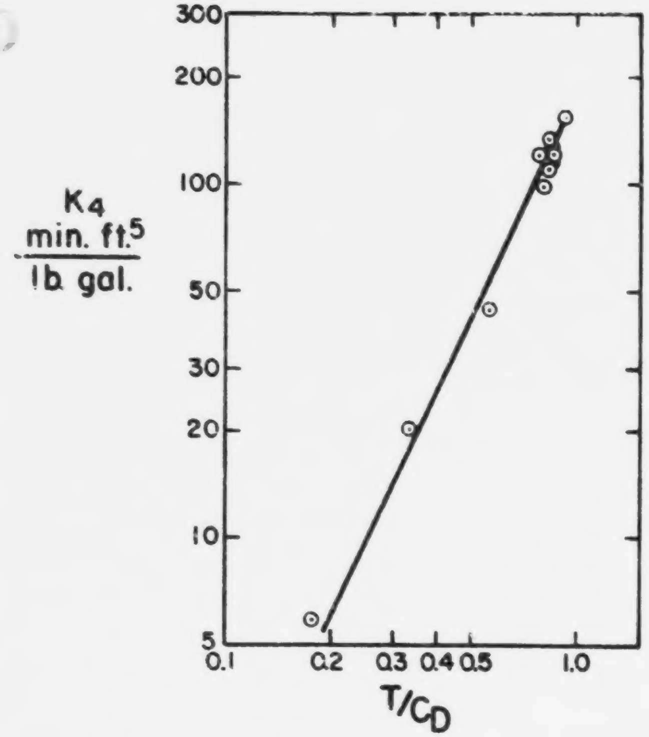
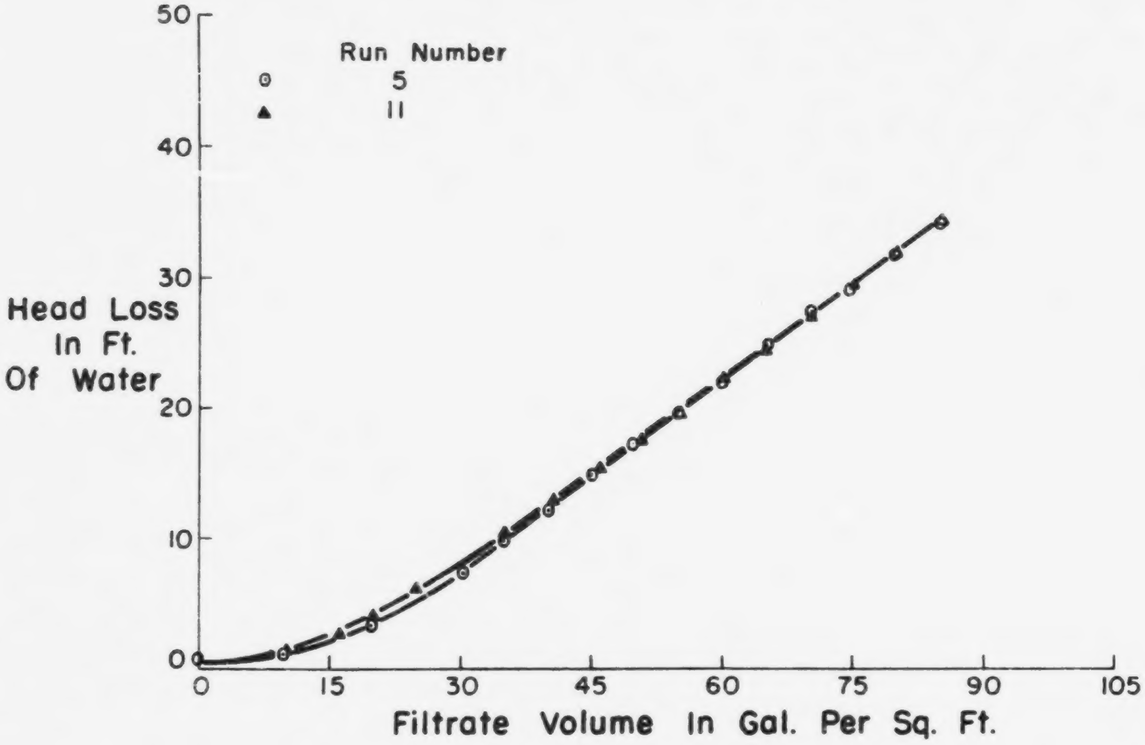


Fig. 9. Plot of impermeability value (K_4) versus ratio of turbidity to body feed concentration (T/C_D) in Series B.

Fig. 10. Reproducibility of head loss curve for Series C.



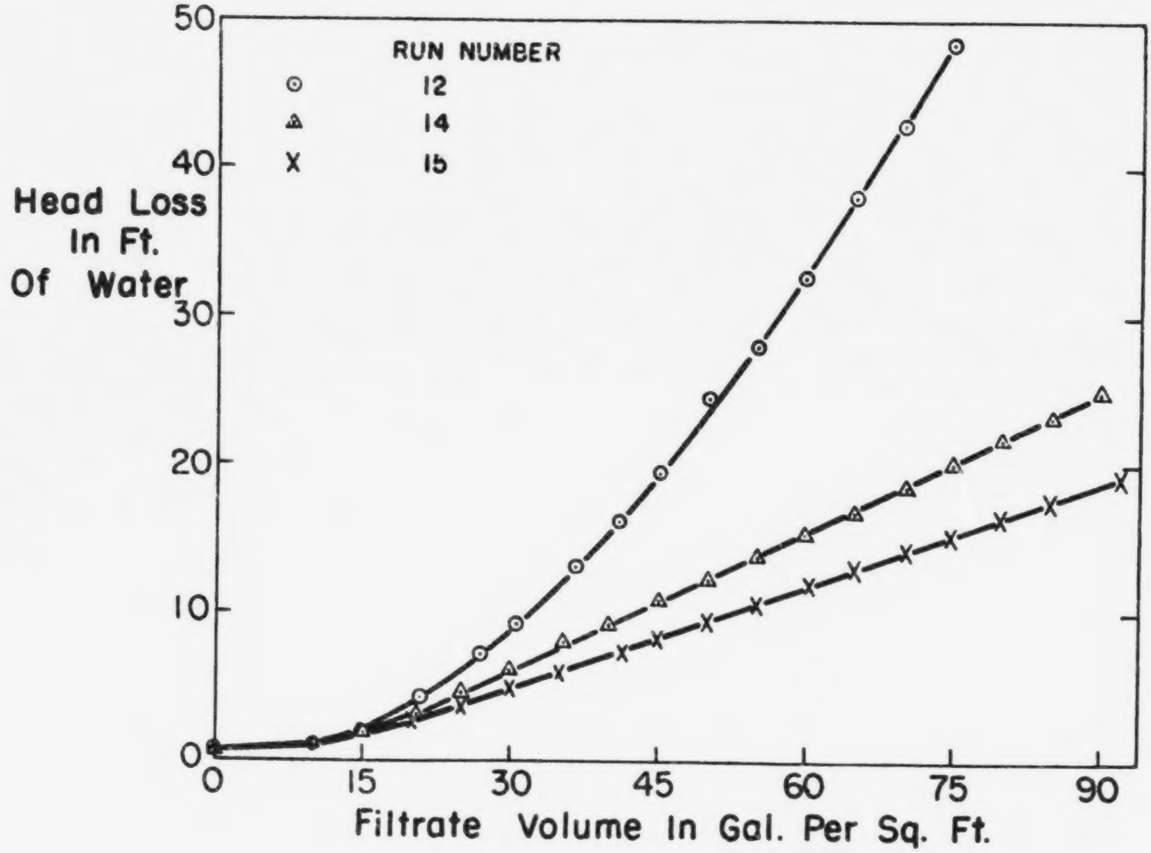


Fig. 11. Variation of head loss for different body feed rates and turbidity level in Series C.

(Fig. 12). The points again give a straight line relationship.

Comparison of K_4 values (Series B and C)

K_4 values obtained in all the runs of series B and C and the corresponding ratios of turbidity to body feed concentration were summarized (Fig. 18). The slope of the straight lines obtained for the two series, B and C, is about the same. Comparison of these two lines shows further that the K_4 value obtained with Hyflo as filter aid is about 3 times the K_4 value for Celite 545 as filter aid for the same ratio of turbidity to body feed concentration. This agrees with the results reported previously using iron floc as suspended solids [9].

WYOMING BENTONITE

Wyoming Bentonite was used as the suspended solids in raw water for conducting two more series of runs, Series D and Series E.

Series D

Hyflow Super-Cel was used as the filter aid in this series. Runs numbered 10, 12 and 14 were all conducted using water with a turbidity of 45 units and an average body feed rate of 350 ppm. The reproducibility of the results was considered acceptable (Fig. 13). However the K_4 values obtained with these runs do not agree well with those of runs numbered 1 through 9, because the turbidity used in the reproducibility runs was far lower than the turbidity of raw water used in those nine runs. Also, runs numbered 1 through 9 were conducted with one lot of diatomite, and runs 10 through 16 were conducted with another lot of diatomite. K_3 values determined were 4.14 and 3.84 for

Fig. 12. Plot of impermeability value (K_4) versus ratio of turbidity to body feed concentration (T/C_D) in Series C.

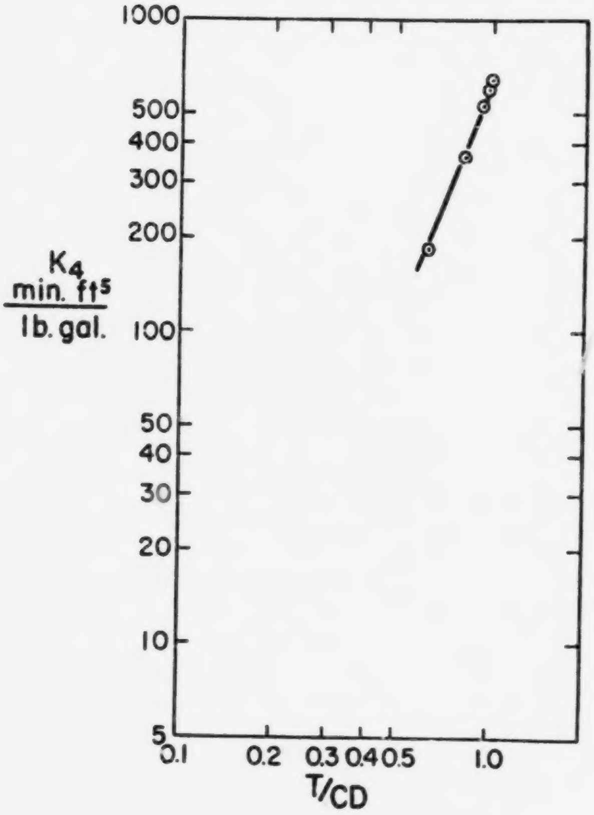
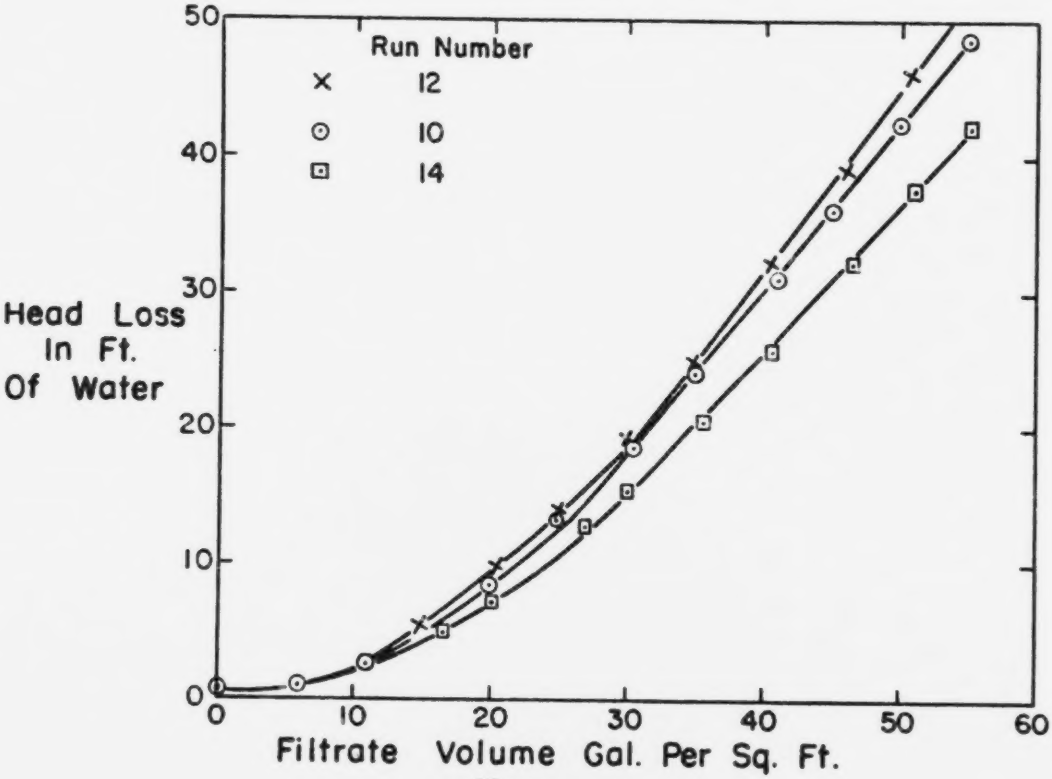


Fig. 13. Reproducibility of head loss curve for Series D.



the first and second lots respectively, a difference of 7.5 percent.

Head loss data from runs numbered 4, 6, 7, 8 and 9 are summarized (Fig. 14). The ratios of turbidity to body feed concentration used in these runs were 0.13, 0.18, 0.22, 0.42 and 0.08 respectively. Run 8 showed a parabolic shaped head loss curve and was not used for K_4 calculation. The straight line relationship between the K_4 values obtained from these runs and the corresponding ratios of turbidity to body feed concentration were determined (Fig. 15). K_4 values obtained in runs numbered 10 through 16 are not included, because they were conducted for some other purpose. These runs are discussed in the next section and the K_4 values are presented (Fig. 17).

Series E

Celite 545 was the filter media in this series of runs. After conducting two runs this series had to be stopped because more than 25 percent of the clay mineral suspended in raw water passed through the filter cake during the two runs.

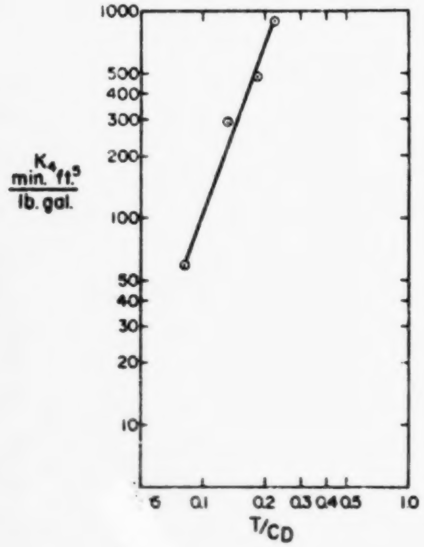


Fig. 15. Plot of impermeability value (K_4) versus ratio of turbidity to body feed concentration (T/C_D) for Runs 1 through 9 of Series D.

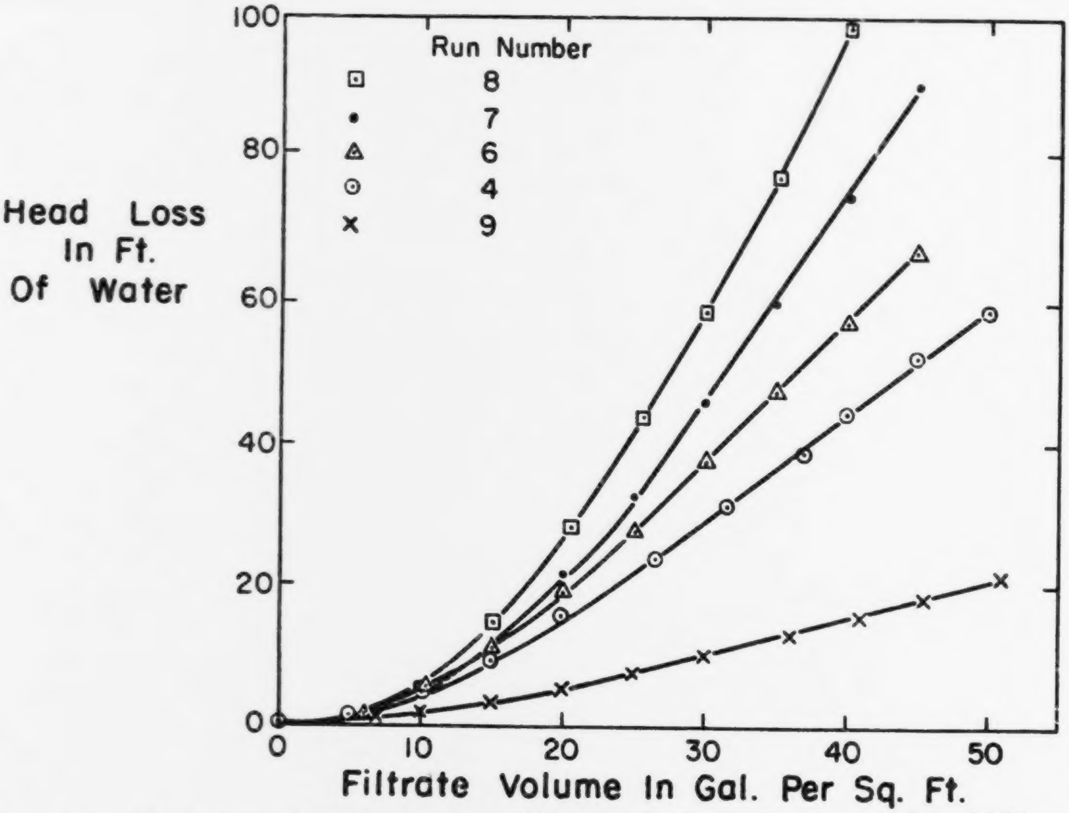


Fig. 14. Variation of head loss for different body feed rates and turbidity levels in Series D.

EFFECT OF TURBIDITY ON K_4 VALUES

Runs 16, 17 and 18 of series B, and 10 through 16 of series D, were conducted to study the effect of the level of turbidity on K_4 values when the ratio of turbidity to body feed concentration was kept almost the same in each series.

Ball clay was used as suspended solids in water, and Celite 545 was used as the filter media in runs 16, 17 and 18 of series B. The ratios of turbidity to body feed concentration used in these runs were 0.823, 0.839 and 0.796 respectively. The turbidity of raw water used was 128, 64, and 100 units respectively. These runs showed that the turbidity had no effect on the K_4 values as long as the ratio of turbidity to body feed was kept the same. This agrees with the previous investigations with water containing flocculent hydrated iron oxide [4, 11].

Wyoming Bentonite was used as the suspended solids in water and Hyflo Super-Cel was used as the filter media in runs 10 through 16 of series D. Run 13 was not completed due to mechanical trouble in the body feeder. The ratio of turbidity to body feed concentration was kept close to 0.13 in all runs except in run 11 in which the ratio was 0.15. The turbidity of raw water used varied from 32.5 units to 123 units. A plot of K_4 values and the turbidity showed an exponential relationship between the two (Fig. 16). This is in contrast with the results obtained with ball clay and in earlier investigations with iron floc [4, 11]. The reason for such a deviation cannot be explained from the data collected. A log-log plot of these K_4 values and the K_4 values of the other runs of series D and the corresponding ratios of turbidity to body feed concentration is shown in Fig. 17. In this figure, it seems that close parallel straight lines could be drawn each representing a small range of turbidity, and vertical lines would represent the K_4 values for the same ratio, but with different turbidities.

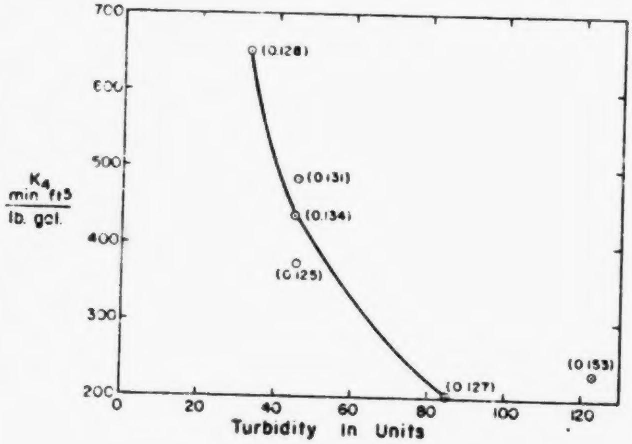


Fig. 16. Variations of impermeability of filter cake (K_4) with turbidity for reasonably constant ratio of turbidity to body feed concentration in series D.

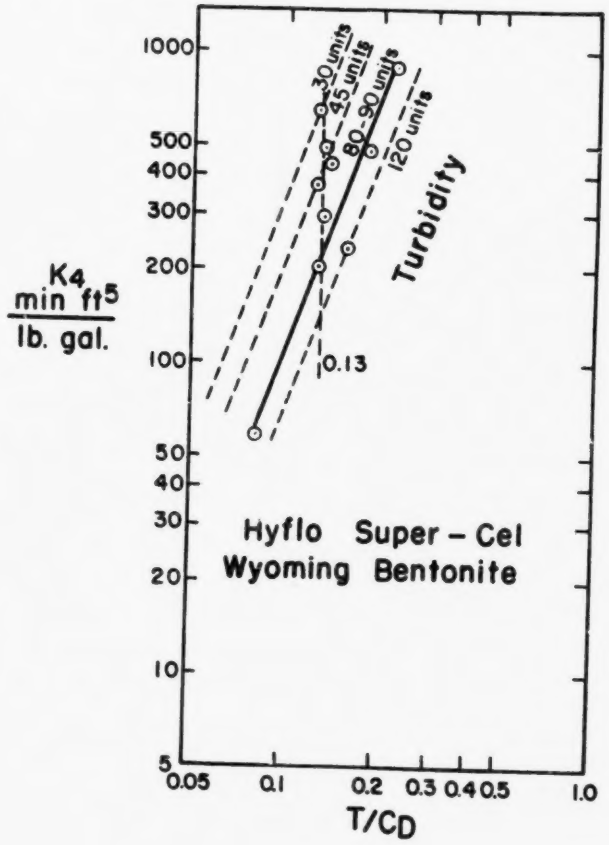


Fig. 17. Plot of impermeability value (K_4) versus ratio of turbidity to body feed concentration (T/C_D) for all runs of Series D.

INTERPRETATION

The K_4 values determined for runs in which Wyoming Bentonite was used as suspended solids were found to be much higher than the K_4 values obtained for the runs in which ball clay was used as suspended solids for comparable turbidity to body feed ratios (Fig. 18). Ball clay and Wyoming Bentonite consist mainly of Kaolinite and Montmorillonite respectively. Attempts were made to find out the reasons for such a difference in K_4 values for the two clay minerals.

Turbidity versus concentration

Turbidity of water is an optical property of the suspension. The optical properties of the two clay minerals, Kaolinite and Montmorillonite, are known to differ from each other [8]. In the diatomite filtration equation developed, the concentration of suspended solids in water and not just the turbidity of water was used [4]. Tests were conducted to establish the relationship between the turbidity of water and concentration of clay mineral suspended in the water. It was expected that replotting the data using suspended solids concentration rather than turbidity might yield closer agreement between the K_4 values for the two clays.

The following method of testing was adopted to determine the relationship between turbidity and the concentration in mg/l. One sample of each clay was dried, weighed, and mixed with distilled water in separate measuring jars. Then the suspensions were air-agitated for about eighteen hours. After this period of time the volumes of the suspension were read, and the

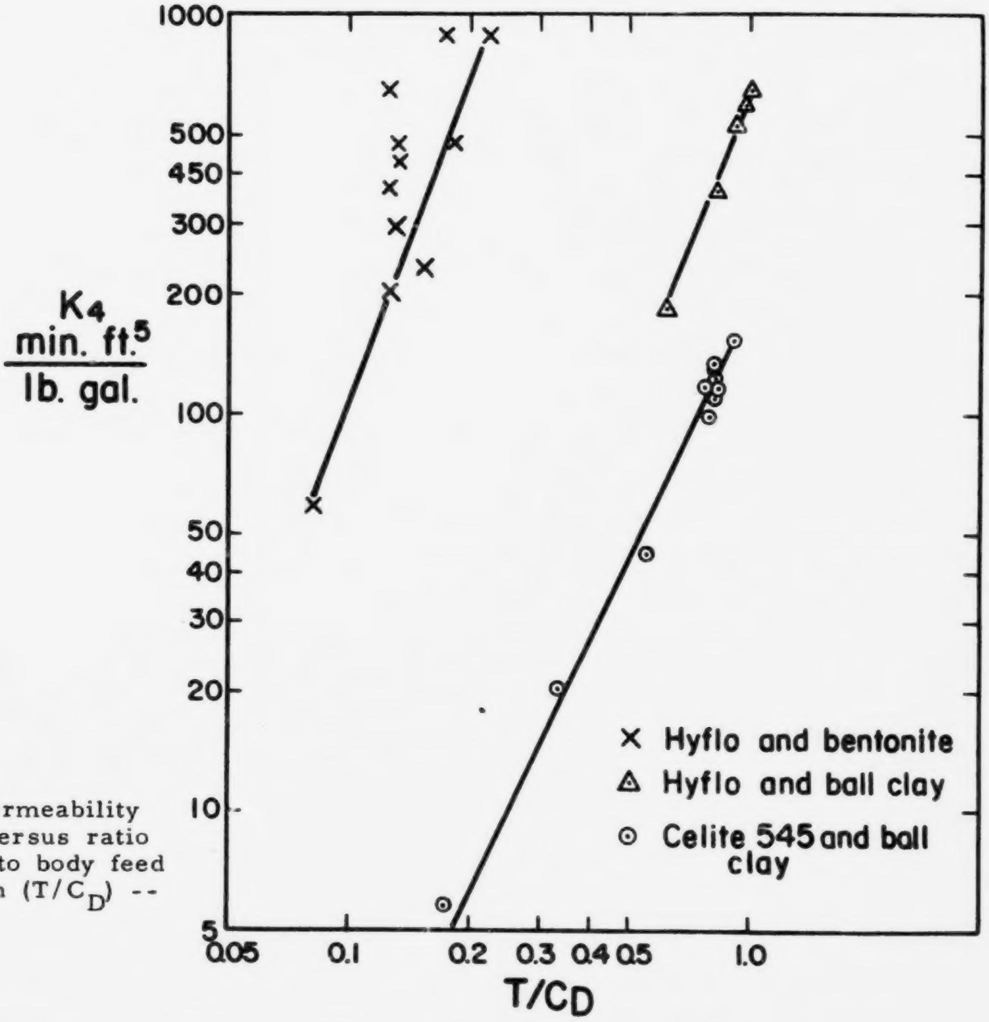


Fig. 18. Plot of impermeability value (K_4) versus ratio of turbidity to body feed concentration (T/C_D) -- summary.

concentrations of the suspensions were calculated. The turbidities of the suspensions were measured with a Jackson Candle Turbidimeter. These stock suspensions were then diluted with distilled water to get different clay concentrations. The turbidities of the various dilutions were measured. The concentrations versus turbidity for each clay were plotted (Fig. 19).

Instead of the turbidity of raw water used for the runs the corresponding concentration of suspended clay minerals was introduced into the calculation of the ratios of concentration of suspended solids to body feed for all the runs (Table II). A summary plot of all of these ratios and the corresponding K_4 values was drawn (Fig. 20). Using concentration instead of turbidity partially closed the gap between the K_4 values for the two different clays.

Particle Size Distribution

Individual particles of Kaolinite and Montmorillonite differ in size from each other. Electron microscope studies show only irregular fluffly masses of extremely small particles in the Montmorillonite, and the probable size of individual particles is reported to be 0.02 to 0.2 microns in plan dimensions by 0.002 microns thick. On the other hand, such studies with Kaolinite place the size of particles around 0.3 to 4.0 microns, in plan dimensions by 0.05 to 2 microns thick[8].

Hydrometer analyses were made to determine the particle size distribution of the two clays (Table III and IV). Also the companies, from whom these clays were obtained, were contacted for information about the particle size distribution and other properties of the clays. These are also tabulated.

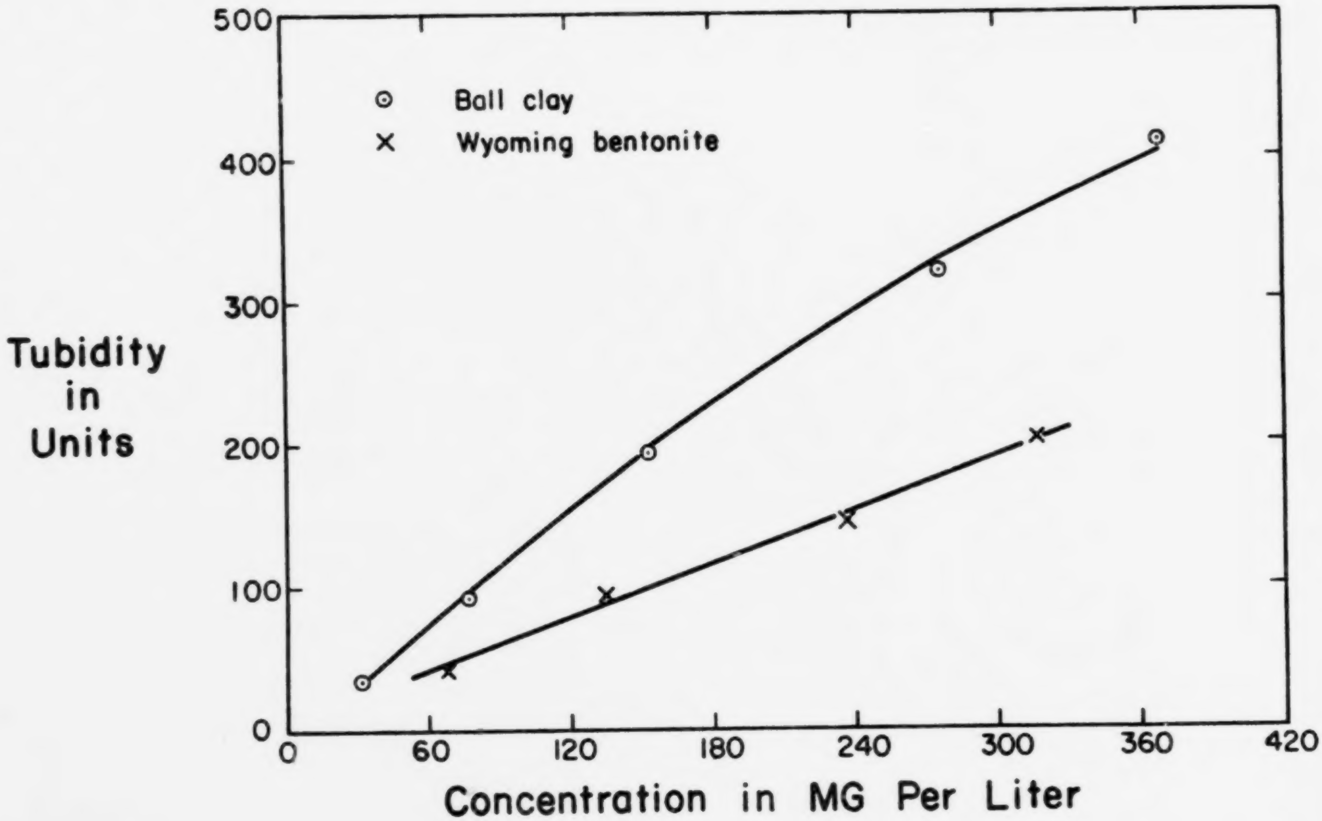


Fig. 19. Plot of concentration versus trubidity for both clays.

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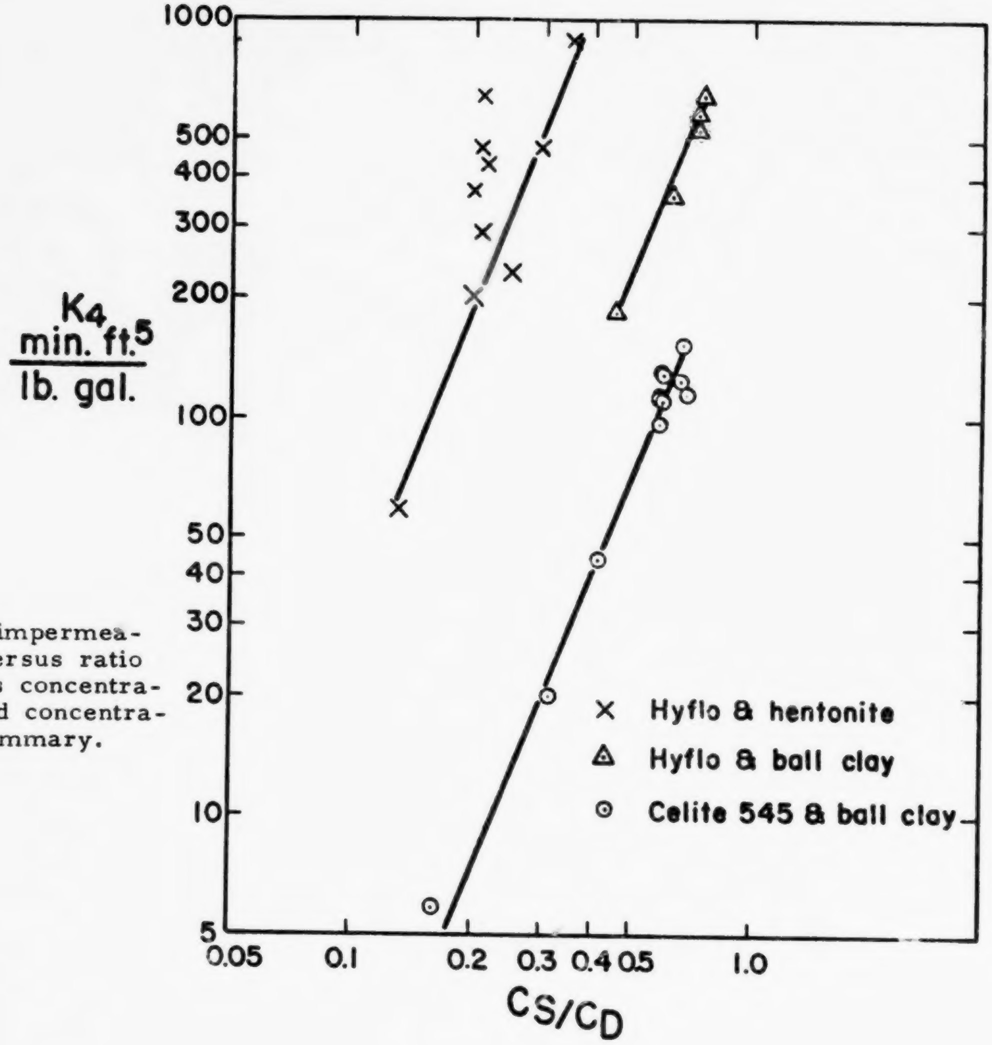

Fig. 20. Plot of impermeability value (K_4) versus ratio of suspended solids concentration to body feed concentration (C_S/C_D) -- summary.

TABLE III. PARTICLE SIZE DISTRIBUTION OF BALL CLAY*

Results of hydrometer analysis		Supplied by the company	
Particle diam in microns	Percent finer	Particle diam in microns	Percent finer
35	100	20	97
24.5	99.1	10	94
15.3	97.2	5	89
9.05	94.5	2	77
6.5	91.7	1	63
4.7	87.9	0.5	47
1.0	71.9	0.2	23
0.75	63.5	0.1	16

*Old Hickory No. 5 Ball clay, Old Hickory Clay Co., Paducah, Kentucky.

TABLE IV. PARTICLE SIZE DISTRIBUTION OF WYOMING BENTONITE*

Results of hydrometer analysis		Supplied by the company	
Particle diam in microns	Percent finer	Sieve size in microns	Percent finer
41.6	100	297	99.5
29.5	97.5	149	98.0
18.6	97.5	106	95.5
10.8	97.5	74	89.5
7.6	97.5	55	80.0
5.4	97.5		
1.1	97.5		

*Black Hills Bentonite, International Minerals and Chemical Corporation, Skokie, Illinois.

The hydrometer analyses were conducted according to the method given in the ASTM Procedure for Testing Soils [2] without any changes for Ball clay, but with few changes for Wyoming bentonite. Since wetting of Wyoming bentonite proved to be difficult, only a 20 gm sample was used instead of the recommended 50 gm sample. Even with that small a sample continuous air-agitation for more than 24 hours was required for wetting and dispersing the clay. Sieve analysis data for the bentonite clay supplied by the company reported that about 20% of particles were larger than 55 microns. This does not agree with our analysis made for this clay. This might be due to the fact that the air-agitation might have broken down the clusters into individual particles of the mineral. But such air-agitation was used also in preparing the raw water suspension for conducting the filtration runs. Therefore, it is believed that the test conducted during this research is a better measure of particles as they existed in the untreated water.

From the results of hydrometer analyses, it was found that Ball clay contained a much greater amount of larger particles than Wyoming bentonite. Higher K_4 values have been obtained when filtering water containing larger sized iron floc [10]. The result of this study seem to be in contrast with those findings.

Such deviations may be due to the peculiar properties of montmorillonite. Montmorillonite and other clay minerals of the same group, when placed in water, readily absorb water and become a thick pasty mass. This property is due to the formation of inter-layer water between the unit cell layers of the mineral and is known as swelling of clays [8]. This swelling property might have taken a predominant part in building up the impermeability of the body feed layer. Two possibilities may exist. The individual clay particle may continue to swell after they have been incorporated in the filter cake. Or, two particles in close proximity in the filter cakes may take on water between them to occupy more void space. Either of these may explain the higher K_4 values, even though Ball clay contains a greater proportion of larger particles than Wyoming bentonite.

Concept of new $[K_4']$

Several attempts were made to account for the unexpected variation of K_4 with turbidity when using water containing Wyoming bentonite, when the ratio of turbidity to body feed concentration was kept the same. The effect of suspended solids on the thickness of filter cake was assumed to be negligible in the development of diatomite filtration equation [4]. Without making that assumption Dillingham reported a similar development of the equation, with a true equation for K_4 as shown below [7].

$$K_4 = \frac{K_2}{d_s} \; \frac{(C_S+C_D)}{C_D} \qquad (11)$$

The concentration of suspended solids and of the body feed diatomite are known in any particular run, but the permeability coefficient (K_2) and the in-place bulk density of the body feed cake (d_S) are unknown factors. A new impermeability value ($[K_4']$), which is equal to the permeability coefficient divided by the bulk density of the cake, has been introduced in this study.

$$\text{ie: } [K_4'] = K_2/\,d_s = K_4 \frac{C_D}{(C_S+C_D)} \qquad (15)$$

New [K_4] values were calculated and reported in the summary of runs (Table II). Also a summary plot of [K_4] values obtained in all the runs was made versus the corresponding ratio of concentration of suspended solids to body feed concentration (Fig. 21). These new [K_4] values are found to be numerically smaller than the corresponding K_4 values obtained for the filter cake (Table II). However, Figs. 20 and 21 show a similar relationship between the impermeability values and the corresponding ratios of suspended solids concentration to body feed concentration. Therefore, the variation of the permeability of filter cakes with turbidity in the case of bentonite cannot be explained even with this new concept of impermeability values.

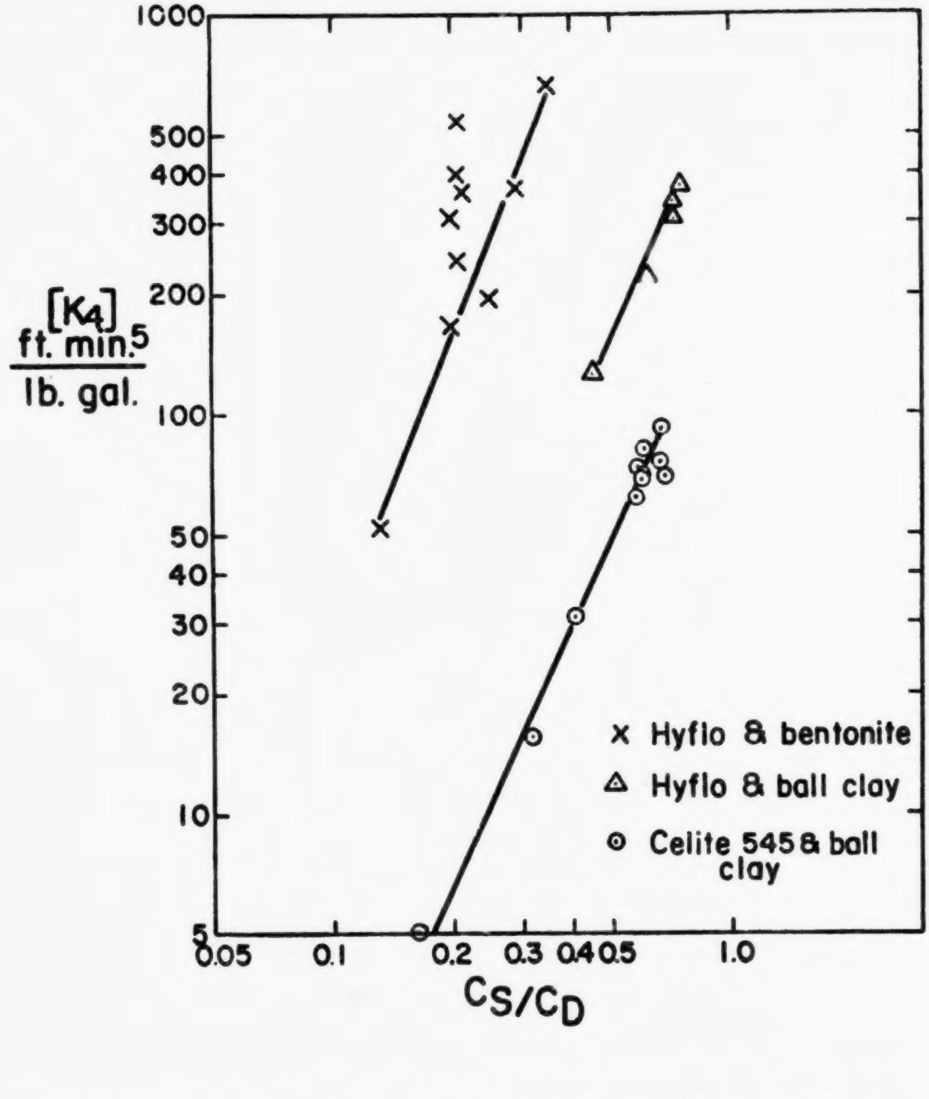

Fig. 21. Plot of modified impermeability value [K_4] versus ratio of suspended solids concentration to body feed concentration (C_S/C_D) -- summary.

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SUMMARY AND CONCLUSIONS

Turbidity in surface waters can result from different suspended solids such as clay minerals, different types of soils, and organic materials. Each type of suspended solids in water when filtered through a diatomite filter shows definite characteristics in head loss development. A diatomite filtration equation recently developed [4] makes possible the determination of the permeability of filter cakes formed when filtering water of varying turbidity. Such permeability information can be used in the rational design of diatomite filtration plants.

Kaolinite and Montmorillonite are two clay minerals often in Midwestern river waters. In this study two clays, consisting mostly of Kaolinite (ball clay) and Montmorillonite (Wyoming bentonite), were used to produce synthetic turbid waters. These waters were filtered through a pilot pressure diatomite filter to evaluate the filtering characteristics of the waters.

Specific objectives of this study are:

1. To determine if acceptable filter effluent quality can be obtained when filtering University tap water to which a clay suspension has been added.

2. To determine the permeability (represented by K_4 values) of body feed layers of different grades of diatomite containing various amounts of different clay minerals.

Celite 545 and Hyflo Super-Cel were used as filter media. Four series of runs were conducted using a different combination of diatomite and clay mineral in each series. Raw water temperature, weight of precoat diatomite and rate of filtration were kept constant throughout the study. The turbidity of the raw water and body feed concentration were so adjusted as to arrive at any desired ratio of turbidity to body feed concentration in each run. The turbidities of the influent and the effluent were continuously monitored during the filter runs. The relationship between head loss and volume of filtrate was observed for all runs, and the impermeability values ($K4$) were determined using this relationship and the filtration equation [4].

Further experiments were conducted to obtain more information about the clay minerals used in this study. They included hydrometer analyses and tests to establish the relationship between the concentration of clay minerals in suspension and the turbidity of the suspension.

The following conclusions have been reached from this study:

1. The straight line relationship between the impermeability value (K_4) and the ratio of turbidity to body feed concentration holds for Kaolinite in spite of any variation of turbidity.

2. The straight line relationship between the impermeability value (K_4) and the ratio of turbidity to body feed concentration does not hold for Montmorillonite when the turbidity of water is not kept constant.

3. The permeability of filter cakes formed while using water containing one clay mineral differs considerably from the permeability of filter cakes obtained using another clay mineral. Impermeability values (K_4) obtained using Montmorillonite as suspended solids are about 75 to 80 times greater for comparable ratios of turbidity to body feed concentration than the values obtained with Kaolinite as suspended solids.

4. Impermeability values (K_4) for Montmorillonite are only 10 times as great as for Kaolinite when they are plotted against the ratio of suspended solids concentration to body feed concentration rather than the ratio of turbidity to body feed concentration. The difference between the two clays is very great and will make a difference in filter operating economy.

5. Ball clay which contains mostly Kaolinite, has a higher proportion of larger particles than Wyoming bentonite, which contains mostly Montmorillonite. The swelling properly of Montmorillonite probably played an important part in building up the impermeability of body feed layer and so raising the K_4 values.

6. The new $\lfloor K_4 \rceil$ concept proves to be of no direct importance to this study, because the variation of the permeability of filter cakes with turbidity in the case of Montmorillonite is not explained even with this new concept.

RECOMMENDATIONS

The following recommendations are the result of this investigation.

1. The effect of suspended solids concentration on the permeability of filter cake should be further studied using different types of suspended solids while keeping the ratio of suspended solids concentration to body feed concentration constant.

2. Different clay minerals including some belonging to the Montmorillonite group should be used in conducting similar studies to find out the effect of swelling of clays on the permeability of filter cakes.

3. Impermeability values (K_4) should be determined using similar conditions for many runs without replacing the diatomite from the body feeder to determine the effect of degradation of diatomite on the permeability of filter cakes.

4. A vibration method of preventing bridging of diatomite in the feed storage hopper should be tested in the hope that it might eliminate the degradation of diatomite caused by the raking arm method now used in the body feeder of the pilot plant.

5. The recirculation pump in the pilot plant should be removed and the main pump itself should be used for both recirculation and filtering.

ACKNOWLEDGEMENTS

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APPENDIX A: DATA SHEET AND CALCULATIONS

K_4 values of each run were determined from the plot of head loss versus filtrate volume for the run. A typical data sheet is shown in Table V. The factors shown above the line are noted either in the beginning, during or after the run. The data collected at regular intervals are shown below the line in columns 1 to 9.

Factors such as the turbidity of raw water, rate of flow, and temperature of the raw water were checked often, and necessary adjustments were made to keep them constant. The rate of body feed was determined by taking two ten-minute samples, one before and one after each run. The two readings and the average of the two were converted into concentration in mg/l, and the concentrations are noted in the data sheet.

The cumulative time of operation in minutes was reported in column 2. The volume of filtrate was calculated by multiplying the time in column 2, by the flow rate (column 7). The level of mercury in the manometer legs is shown in column 3 and column 4 and the head loss in inches of mercury is in column 5. The readings in column 5 were converted into head loss in ft of water at the operating temperature, and these were reported in column 6. The data in column 6 and column 7 were used to plot head loss versus filtrate volume.

The total head loss developed is the sum of the head loss through the precoat layer and the head loss through the body feed layer.

$$H = H_1 + H_2$$

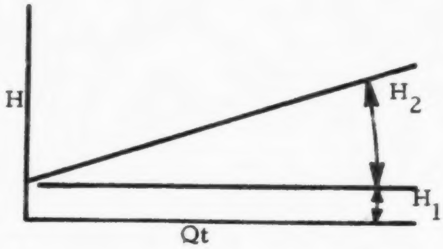
From the diatomite filtration equation, head loss through the body feed layer,

$$H_2 = K_4 C_D Q^2 t \times 8.33 \times 10^{-6}$$

where: H = Total head loss in ft of water
H_1 = Head loss through precoat layer in ft of water
H_2 = Head loss through body feed layer in ft of water
K_4 = Impermeability value for the body feed layer in $\dfrac{\text{min. ft}^5}{\text{lb. gal}}$
C_D = Concentration of body feed in mg/l
Q = Rate of flow in gpm/sq. ft.
t = Time of filtration in minute.

Therefore, $K_4 = \dfrac{H_2 \times 10^6}{C_D Q^2 t.\ 8.33}$

In a theoretical head loss curve as following



the slope of the line obtained is equal to H_2/Qt.

Therefore K_4 = Slope of the line $\times \dfrac{10^6}{8.33\ C_D Q}$

The slope of the head loss curve for the run shown in Table V, was found to be 0.147. Since the concentration of body feed and flow rate was 132.7 mg/l and 1 gm/sq. ft, K_4 value was determined to be

$$K_4 = 0.147 \times \frac{10^6}{8.33 \times 132.7 \times 1.0}$$

$$= \underline{132.5}$$

The ratio of turbidity (T) to body feed concentration was determined from the average turbidity and body feed concentration.

$$T/C_D = \frac{108}{132.7} = \underline{0.815}$$

Next, from the relationship between the turbidity and concentration of suspended solids shown in Fig. 17, the corresponding concentration of suspended solids (C_S) was found to be 79.0 mg/l. From this value, the ratio of suspended solids concentration to body feed concentration was determined.

$$\frac{C_S}{C_D} = \frac{79.0}{132.7} = 0.595$$

The new $[K_4]_{C_D}$ developed during this study is equal to

$$K_4 \frac{C_D}{(C_S + C_D)}$$

$$[K_4] = 132.5 \quad \frac{132.7}{79.0 + 132.7} = \underline{83.1}$$

The modified diatomite filtration equation has α_1 and α_2 as impermeability values instead of K_3 and K_4.

$$\alpha_2 = \frac{K_4 \cdot gd}{6.26 \times 10^{-9} \mu}$$

where: α_2 = the average specific resistance of the body feed layer of the filter cake through which a pressure drop exists in $ft^2/lb. sec^2$

μ = absolute viscosity in centipoise
d = bulk density of water in lb/gal
g = gravitational constant in ft/sec^2

Since the raw water temperature was known to be 60°F, the absolute viscosity and the bulk density of water were found to be 1.1241 centipoises and 8.337 lb/gal respectively from chemical tables. Therefore:

$$\alpha_2 = \frac{132.5 \times 32.2 \times 8.337}{6.26 \times 10^{-9} \times 1.1241}$$

$$= 5.05 \times 10^{12}$$

TABLE V. DATA SHEET FOR A TYPICAL RUN

Run no. B_8,
June 27, 1964
Body feed
Before the run: 135.8 mg/l
After the run: 129.6 mg/l
Average: 132.7 mg/l

Grade	Celite 545
Precoat	0.15 lb/ft^2
Rate of flow	1.0 gpm/ft^2
Raw water temp.	60°F
Clay	Ball Clay
Average influent turbidity	108 units
Average effluent turbidity	0.05 unit

1 Clock time	2 Time in min.	3 Manometer reading in inches of mercury	4	5	6 Head loss in ft of water	7 Volume of filtrate in gal/ft^2	8 Turbidity in units	9
		Left	Right	Difference			Influent	Effluent
10.05	0	0.10	0.21	0.11	0.12	0	108	---
10.35	30	0.20	0.73	0.93	0.98	30	106	---
11.05	60	1.78	2.32	4.10	4.31	60	105	0.03
11.35	90	3.70	4.22	7.92	8.31	90	107	0.05
12.05	120	5.68	6.22	11.90	12.50	120	108	0.05
12.36	151	7.78	8.32	16.10	16.91	151	108	0.05
1.05	180	9.70	10.26	19.96	20.96	180	108	0.05
1.35	210	11.85	12.25	24.10	25.32	210	109	0.05
2.05	240	13.80	14.25	28.05	29.45	240	108	0.05

$T/C_D = \frac{108}{132.7} = 0.815$

$K_4 = 132.5$

APPENDIX B: HEAD LOSS DATA

Total flows and the head loss values of all the valid runs (except those which are presented in figures) are tabulated below:

Run B_1 Flow (Gal/sq ft.)	Head Loss (ft)	Run B_2 Flow	Head Loss
30	0.44	30	0.68
60	2.05	60	2.63
90	4.78	90	5.15
120	7.93	120	7.35
150	11.08	150	9.35
180	16.59	180	11.29
210	30.03	210	13.02

Run B_4 Flow	Head Loss	Run B_5 Flow	Head Loss
60	0.71	60	2.90
120	1.43	90	6.82
180	2.03	120	10.60
240	2.66	150	15.34
300	3.26	180	19.52
360	3.86	210	24.23

Run B_6 Flow	Head Loss	Run B_7 Flow	Head Loss
60	5.93	30	2.46
90	12.19	60	9.92
120	18.70	90	18.40
150	25.66	120	30.50
180	34.05	150	46.60
210	41.27	165	54.35

Run B_{11} Flow	Head Loss	Run B_{16} Flow	Head Loss
30	0.91	60	3.17
60	5.27	90	6.30
90	10.19	120	11.00
120	15.88	150	14.55
150	22.00	180	19.40
180	28.25	210	23.80

Run B_{17} Flow	Head Loss	Run B_{18} Flow	Head Loss
60	1.28	60	1.85
90	2.84	90	3.92
122	4.72	120	6.40
151	6.67	155	9.50
180	8.90	180	11.81
210	11.23	210	14.80

Run C_1

Flow	Head Loss
15	2.73
30	16.90
35	32.20
40	52.00

Run C_2

Flow	Head Loss
15	4.39
30	33.81
35	52.08
38	63.84

Run C_3

Flow	Head Loss
15	2.53
31	12.30
42	20.48
51	27.55
60	35.40
70	44.50
80	53.80

Run C_4

Flow	Head Loss
16	1.67
30	5.38
40	8.56
50	11.88
60	15.19
70	18.21
80	21.60

Run C_6

Flow	Head Loss
25	6.45
35	12.71
45	19.85
55	27.41
65	35.60
75	43.60
85	52.50

Run C_7

Flow	Head Loss
10	0.99
20	3.15
30	8.46
40	14.18
50	21.22
60	27.84
70	34.82

Run C_9

Flow	Head Loss
10	1.21
20	8.33
30	16.30
40	28.81
50	43.40
60	60.09

Run C_{10}

Flow	Head Loss
15	2.80
25	7.90
37	15.22
45	20.25
55.5	27.80
65	34.35

Run C_{13}

Flow	Head Loss
15.5	2.12
25	7.66
35	16.38
45	27.84
55	42.00
66	60.15

Run D_1

Flow	Head Loss
10	12.40
15	22.90
20	35.00
25	50.70
29	65.20

Run D_2

Flow	Head Loss
10	7.25
15	16.90
20	28.50
25	44.70
30	63.30

Run D_3

Flow	Head Loss
11	7.30
17	20.25
20	28.30
25	43.95
30	62.40

Run D_{11}

Flow	Head Loss
5.5	1.60
15.5	7.41
25	17.35
35	31.50
45	46.90
55	63.21

Run D_{15}

Flow	Head Loss
10	2.67
20	8.81
30.5	17.90
41	29.07
51.5	40.60
60	50.55

Run $_{16}$

Flow	Head Loss
10	1.89
20	8.09
30.5	18.41
40	30.00
50	43.80
60	57.20

Run E_1

Flow	Head Loss
20	1.80
40	8.17
60	16.46
81	26.25
100	36.45

Run E_2

Flow	Head Loss
10	0.41
30	2.57
50.5	6.93
71	12.97
93	20.78
110	27.83

PART II

COATINGS FOR FILTER MEDIA

D. E. Burns
C. S. Oulman
E. R. Baumann

Progress Report

COATINGS FOR FILTER MEDIA

by

Donald E. Burns
Charles S. Oulman
E. Robert Baumann

United States Public Health Service
Division of Water Supply and Pollution Control
Research Grant WP-00196

Project 549-S

Municipal Diatomite Filters

August 15, 1965

IOWA
ENGINEERING
EXPERIMENT
STATION

IOWA STATE UNIVERSITY
of Science and Technology / Ames, Iowa

COATINGS FOR FILTER MEDIA

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This investigation was supported by the Iowa Engineering Experiment Station in part through funds made available by Research Grant WP-00196 and Research Fellowship 5-F1-WP-26,003 from the Division of Water Supply and Pollution Control, Public Health Service.

August 15, 1965

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INTRODUCTION

Diatomaceous earth is used as a filter media in the purification of water by filtration. Some of the uses are the filtration of swimming pool water, the filtration of public water supplies which have relatively low turbidities[2], and the filtration of water for such industrial processes as beer making.

During World War II a major emphasis was placed on developing a water filter to produce potable water for use by American troops in the South Pacific. At that time there was a need for a portable filter plant using a filter media which would mechanically strain out the encysted form of Endamoeba hystolitica, the causative agent of amoebic dysentery, which is not removed by rapid sand filtration nor killed by ordinary chlorination procedures. It was established that diatomite filters would satisfy this need.

Since the war much research pertaining to diatomite filter media and the filtration of water through diatomite filter media has been conducted by industry and government. The knowledge resulting from this research has made it possible for public health officials to accept at an increasing rate the use of diatomite water filters for the purification of public water supplies. Research has extended knowledge in such areas as the design requirements of such filtration plants and the properties of the diatomaceous earth itself.

Diatomite, or diatomaceous earth, is a mineral which results from an accumulation of minute, siliceous, fossil shells of diatoms which are a class of algae. It is largely amorphous silica and is light in weight. The dry weight of diatomite in a filter cake is 13 to 18 lb/ft^3 and the porosity is 85 to 90%[14]. Its structure and chemical inertness makes it a desirable filter media.

When placed in water diatomite has an electronegative surface charge resulting from preferentially adsorbed anionic potential determining ions. Most naturally occurring colloidal particles, which need to be removed from public water supplies, also have an electronegative surface charge for the same reason. Many electronegative colloids not removed by mechanical straining will pass through electronegative diatomite filter media. Increased efficiency in removal of colloidal particles has been obtained by using a diatomite filter media electropositively coated with a layer of precipitated hydrated aluminum oxide (Figs. 1-3)[2]. The electropositive coating was produced by mixing the diatomite in a solution of aluminum sulfate (alum)[2]. A disadvantage of using alum coated diatomite filter media is the decrease in permeability observed for this coating material.

Aluminum, the trivalent positive metallic ion in alum, functions as a coagulant by lowering the zeta potential of electronegative particles. Certain cationic organic polyelectrolytes can function as a coagulant the same as alum, for certain types of waters[3]. This similarity in the electrokinetic properties of hydrated aluminum oxide (alum in aqueous solution) and cationic organic polyelectrolytes prompted consideration of these organic compounds for coating materials. An investigation was made to determine some of the characteristics of diatomite filter media coated with cationic organic polyelectrolytes. Specific objectives of this investigation were:

1. To determine the zeta potential of diatomite filter media coated with various amounts of cationic organic polyelectrolytes.
2. To determine an impermeability coefficient of diatomite filter media coated with various amounts of cationic organic polyelectrolytes.
3. To determine the relationship between the zeta potential of a diatomite filter media coated with a cationic organic polyelectrolyte and the pH of the water being filtered.

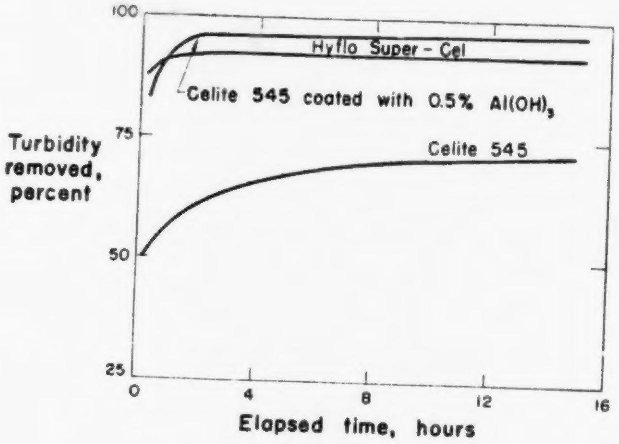


Fig. 1

Effect of an electropositive coating of aluminum hydrate on turbidity removal from Raritan River water (2)

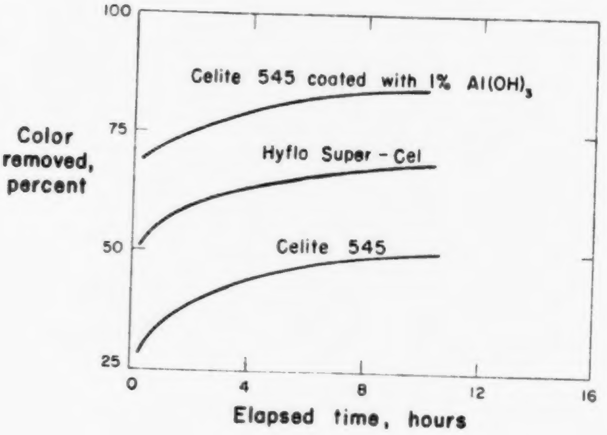


Fig. 2

Effect of an electropositive coating of aluminum hydrate on color removal from Raritan River water (2)

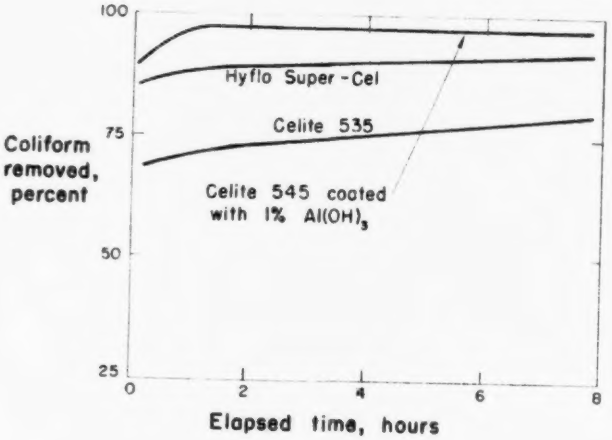


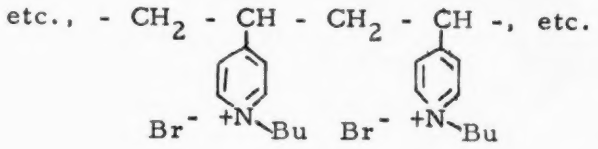
Fig. 3

Effect of an electropositive coating of aluminum hydrate on coliform removal from Raritan River water (2)

BACKGROUND INFORMATION

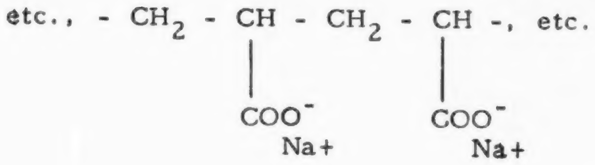
Organic Polyelectrolytes

Organic polyelectrolytes are high molecular weight polymer compounds which contain ionic substituents in their monomer units. These substances combine the properties of electrolytes and polymers. Polyelectrolytes are categorized as cationic or anionic depending on the sign of the charge at their ionized sites. An example of a cationic polyelectrolyte is poly-(4-vinylpyridine) quarternized with butyl bromide:



This compound is a strong electrolyte because the quarternary ammonium ion claims the bromide ion only by electrostatic forces[9].

An example of an anionic polyelectrolyte is sodium polyacrylate:



$$\text{etc.,} - CH_2 - \underset{\substack{|\\ COO^- \\ Na+}}{CH} - CH_2 - \underset{\substack{|\\ COO^- \\ Na+}}{CH} -\text{, etc.}$$

The two substances shown above are considered linear polymers.

In addition to the cationic and anionic classification there is the nonionic polyelectrolyte, so called because it does not show electrophoresis. The nonionic polyelectrolyte can be visualized as containing nearly equal numbers of anionic and cationic charged sites.

Zeta Potential

When a negatively charged colloid is suspended in a liquid, positive ions from the bulk of the solution are attracted to the colloid's surface and form an immobile layer around the colloid. Zeta potential is a measure of the electrical potential between the ions in the immobile layer and the ions in the bulk of the solution a distance of a few hundred Angstroms from the surface of the colloid. In many respects the effects of zeta potential begin where the effects of gravity become inconsequential[16]. This is especially true for particulate matter of colloidal dimensions.

When a liquid is passed (or forced) through a porous media an electrical potential is developed. This electrical potential, called streaming potential, is related to the zeta potential by the following[15]:

$$\zeta = \frac{4\pi k E \eta}{DP}\left[\frac{1}{R} + \frac{4\lambda s}{\phi}\right] \qquad (1)$$

where: ζ = zeta potential

4π = a constant

k = a proportionality constant relating electrostatic units to practical electrical units equal to

$$8.98776 \times 10^{9} \frac{\text{Newton meters}^2}{\text{Coulombs}^2}$$

E = streaming potential

η = absolute viscosity of the water

D = dielectric constant of the water

P = pressure difference across the porous media

λ_s = specific surface conductance

R = resistivity of the water

ϕ = mean particle size (diameter)

Impermeability Coefficient

When water is forced through a porous media, energy is lost from the water due to the resistance of the media to the flow of water. In the modified form of the diatomite filtration equation the specific resistance of the filter media to the flow of water is included in the impermeability coefficient, K_3[1]. The head loss across a precoat layer of diatomite is given by[1]:

$$H = K_3 Q W_1 \qquad (2)$$

where: H = head loss through the filter cake

K_3 = impermeability coefficient

Q = flow rate

W_1 = weight of the filter cake

K_3 can be determined by depositing a known weight of diatomite on a filter septum and measuring the head loss required to attain a given flow rate. In actual practice three to five sets of data relating head loss to flow rate are taken, and this data is plotted on arithmetic graph paper. The resulting slope of the straight line is used as the value for $\frac{H}{Q}$ in the following:

$$K_3 = \frac{H}{Q} \frac{1}{W_1} \qquad (3)$$

The impermeability coefficient varies with viscosity and the bulk density of the water being filtered in the following manner[1]:

$$K_3 = C \frac{\eta a}{gd} \qquad (4)$$

where: η = absolute viscosity of the water being filtered

a = average specific resistance of the filter media to the flow of water

g = the gravitational constant

d = the bulk density of the water

C = proportionality constant

The variation of K_3 with respect to bulk density is quite small, and so Eq. 3 is modified to provide a consistent value for K_3, at a standard temperature:

$$K_3 = \frac{H}{Q\,W_1} \frac{\eta_o}{\eta_t} \qquad (5)$$

where: η_o = absolute viscosity of water at a standard temperature

η_t = absolute viscosity of water at the test temperature

Equation 5 was used to compute impermeability coefficients, K_3, in this investigation. The standard temperature was taken as 20.3°C at which η_o = 1.00 centipoises.

LITERATURE REVIEW

Electropositive Coatings for Diatomite

In 1936 a process was patented for giving diatomite an electropositive coating to improve its value as a filter media[6]. This patent covered the process of giving a base material of discrete particles in aqueons solution electropositive characteristics by coating the surface of the particles with an electropositive substance. To illustrate the process comminuted calcined diatomaceous earth was coated in a solution of aluminum sulfate with hydrated aluminum oxide. The aluminum sulfate and diatomite were mixed gently as a slurry with the pH adjusted to 5.5 with sodium hydroxide. The coated diatomite was then washed with distilled water to remove any excess of either the chemicals used or soluble by products of the reaction. The washed product was then dried at about 80°C. using a mild dispersing action to inhibit caking. It was observed that:

> "Filtering a turbid river water in a comparable manner, first, with a conventional filter aid and, second, with the same filter aid electropositively coated, and observing the filtrates with a Tyndallometer, there was noted a more pronounced Tyndall effect in the filtrate from the conventional filter aid than from the electropositive aid."

Twenty-five years later filtration results using diatomite coated with aluminum sulfate to filter Raritan River water were reported[2]. Some of these results are presented in Figs. 1-3.

With respect to turbidity removal (Fig. 1) it was reported that:

> "When using the $Al(OH)_3$-coated Celite 545 with plant-scale filters at the Johns-Manville Research Center at 1.0 gpm/ft^2 to filter 450 gpm of Raritan River water having turbidities in excess of 50 units and ranging up to 175 ppm (sic), filter cycles more than eight hours in length to terminal head losses of 25 psi produced filtered water of excellent clarity and color. Previously, use of uncoated, or 'regular', filter aids was limited in this plant to not more than 15 units of turbidity in the raw water to limit average finished water to about 1.0 unit."

Figures 2 and 3 show the increased efficiency in removal of color and coliforms when using $Al(OH)_3$-coated Celite 545 as opposed to using "regular" filter aids. It was noted that in some cases five to not more than ten minutes contact time between the electropositively coated filter aid and the color containing water had appreciably improved color removal.

It was emphasized that the electropositive coatings were prepared at the time and place of use rather than during the manufacturing process. No data were presented concerning the zeta potential or the permeability of the coated diatomite filter cakes.

Other research has shown in a quantitative manner that coating diatomite in solutions of $AlCl_3$, $Al_2(SO_4)_3$, and $Fe_2(SO_4)_3$ produces an electropositive filter media[15]. Coating diatomite, Celite 545, with a cationic organic polyelectrolyte also produced an electropositive filter media.

Diatomite coated with alum was electropositive when analyzed by streaming potential measurements but was not electropositive when analyzed by electrophoretic measurements. It was concluded that the streaming potential method of determining zeta potential is the only method which can differentiate accurately between negative and positive zeta potentials as they pertain to the effective charge on a filter cake.

Use of Polyelectrolytes in Water Treatment

As long ago as about 2000 B. C. a number of vegetable substances, notably the seed of *Strychnos patatorum*, were used for clarifying water[3]. These natural polyelectrolytes were not used to any great extent in the treatment of public water supplies until the past decade. In the last few years, however, the use of natural and synthetic polyelectrolytes as coagulant aids with convential coagulants, such as aluminum sulfate, has increased.

When used in conjunction with common metal coagulants, polyelectrolytes yield large, dense floc which settles rapidly. Frequently, turbidity removal is also improved. With some waters, coagulation may be obtained with the addition of a polyelectrolyte without the joint use of a metal coagulant. For those waters, then, polyelectrolytes are coagulants in their own right in addition to being coagulant aids[3].

In recent years at least one new water treatment plant has been designed where the use of polyelectrolytes as a coagulant aid was incorporated in the design of the treatment process[17].

In 1960 the use of polyelectrolytes as filter conditioners or filter aids for water filtration with sand-anthracite filter media was reported[5]. *Separan NP-10*, a nonionic polyacrylamide, and *Hogan coagulant Aid-2*, a polysaccharide, were reported as the most effective polymers for filter conditioning. The polyelectrolytes were applied just before filtration to discourage complete adsorption of the polyelectrolytes on the floc particles. Therefore, it was postulated that the organic compounds acted to bind the floc particles to each other and to the filter media. The materials bonded to the filter media were removed by normal backwashing procedures.

Addition of these polyelectrolytes before filtration with sand-anthracite filters resulted in lower effluent turbidities but increased rate of head loss buildup[4].

In the Microfloc process of water treatment polyelectrolytes are used as filter conditioners. At Philomath, Oregon, a pilot plant using the Microfloc process is being evaluated as a tertiary treatment method for the effluent from a high-rate trickling filter waste treatment plant. The operators of this pilot plant have used cationic, anionic, and nonionic polyelectrolytes. They apparently had the most success in using Separan, a nonionic polyelectrolyte. Using cationic polyelectrolytes resulted in increasing head losses, and in a poor quality filter effluent.

In one application Separan was used as a filter conditioner in removing iron oxide floc formed by chlorination and aeration of deep well water from a Southwest municipality[12]. The filter influent to anthracite filters contained from 3 to 5 ppm of iron. The use of Separan reduced the effluent iron content from a maximum of 0.65 ppm at the end of 12 hours service with no Separan, to a maximum of only 0.06 ppm at the end of 24 hours service with 0.04 ppm of Separan.

In another application the use of Separan reduced filter influent turbidity from 2 to 3 ppm to an effluent turbidity of zero; effluent turbidities were as high as 0.5 units when Separan was not used[12].

> "The use of large-grained filter media, when using a filter aid, offers the possibility of removal of a high degree of suspended solids without a corresponding high increase in rate of head loss."[12]

Studies at the Water Works Park Filter Plant in Detroit were made using Separan as a filter conditioner[10]. The existing rapid sand filters, with an effective sand size of 0.60 mm, were operated at 2.5 gpm/ft^2 to treat water with turbidities ranging from 2 to 15 units, with water temperatures ranging from 33° to 70°F. When no Separan was used filter effluent turbidities of 0.3 to 0.4 units were observed. When 0.020

ppm of Separan was used the filter effluent turbidity was reduced to less than 0.1 units. The reduction in filter effluent turbidities was obtained at the expense of increased rate of head loss buildup. It was concluded from the Detroit studies that:

> "The practical use of a polyelectrolyte as a filter aid would be limited to plants which can not consistently produce a satisfactorily clear water because of some inadequacy in the plant design and where there is no problem with short filter runs, as some filter efficiency must be sacrificed for the sake of the improved clarification."

It was also found in the Detroit studies that feeding large concentrations of Separan in an attempt to eliminate breakthrough of turbidity resulted in only temporary reduction of effluent turbidity and sharply increased head losses. Therefore, slug feeding of polyelectrolytes to control breakthrough would not be practical.

In discussing the effect of a polyelectrolyte on the removal efficiencies of coliform bacteria, virus, carbon, or floc using mixed-bed filters, one investigator reported that increased floc strength was important in achieving satisfactory removals[18].

Another investigator has reported that surface active coating agents or filter conditioners were used to improve filtration efficiencies[11]. When high concentrations of activated carbon slurry were used to combat taste and odor problems, undesirable amounts of carbon appeared in the rapid sand filter effluent. The effective sand size in the filters was 0.65 mm. A satisfactory filter effluent could be produced when 1 to 4 ppm of Nalco 110 or Catalyzer were fed continuously as a filter conditioner. Wash water costs were slightly increased and filter run lengths were reduced by 60 to 70%[11].

During warm weather the filter conditioner was applied just after sedimentation; during cold weather the conditioner was applied at the center of the coagulation basin[11]. It was assumed that the filter conditioners coated the surface of the filter media and resulted in an adsorptive surface. It is unlikely that the filter media was coated when the organic compounds were fed at the center of the coagulation basin. Rather, one would expect that the compounds coated the particulate matter and built up floc by a bridging mechanism, making the floc more filtrable.

Summary

The use of electropositive coatings is not new. Diatomite with electropositive coatings of $Al(OH)_3$ provide greater removal of turbidity, color, and bacteria than uncoated diatomite filter media.

Organic polyelectrolyte filter conditioners have been used in a wide variety of conditions pertaining to filter media composition and size, filtration rate, and type of water being treated. Increased efficiency in the removal of particulate matter normally results in increased rate of head loss build-up. It has not been established whether polyelectrolyte filter conditioners aid the filtration process by producing tougher, more filterable, floc or by producing an adsorptive surface active coating.

LABORATORY INVESTIGATIONS

Laboratory investigations were conducted to determine the impermeability coefficient, K_3, and zeta potential, ζ, of diatomite filter cakes coated with various amounts of cationic polyelectrolytes. Tests were also conducted to determine the effect of the pH of the water being filtered on the zeta potential of a diatomite filter cake coated with a given amount of cationic polyelectrolyte. The typical operational procedure and the apparatus used in these investigations are described in Appendix A.

No effort was made to determine the most efficient or effective method of coating the filter media. A quick and convenient method of coating diatomite with polyelectrolyte was used. Five grams of diatomite and about two-tenths of a liter of deionized water were mixed in the precoat pot of the pressure filter permeameter with a magnetic stirring device. Polyelectrolyte was then pipeted from a stock solution into the diatomite slurry, and the mixture was kept in suspension for about 15 minutes. The diatomite slurry was then pumped into the filter and deposited on the filter septum, as explained in Appendix A, and then the desired tests were made.

Celite 545, a product of Johns-Manville, was used in all laboratory tests. It was chosen because it produces a permeable cake, and some decrease in permeability was expected to occur when the filter media was coated.

Three commercially available cationic polyelectrolytes were used in these investigations:

Polyelectrolyte A (Purifloc 601 a product of the Dow Chemical Co.) is a highly viscous, dark amber liquid which has a cationic charge charge resulting from a polyamine chemical nature[8]. It is completely water-soluble and has a pH of from seven to eight.

Polyelectrolyte B ("UCAR" Resin C-149 a product of the Union Carbide Chemicals Co.) is a white granular solid which is hygroscopic and water soluble. It has a high molecular weight and is cationic in charge characteristic[20].

Polyelectrolyte C, (Reten 205, a product of the Cellulose and Protein Department of the Hercules Powder Co.) is a cationic, high-molecular-weight, synthetic co-polymer. It is a white, finely divided powder that dissolves in hot or cold water to give a clear solution of high viscosity[13]. The cationic characteristic arises from a quaternized nitrogen which is attached to the slightly branched, saturated carbon-carbon bond, polymer backbone through an ester linkage. Reten 205 has a molecular weight in excess of one million and has a molecular weight per cationic charge of approximately 1600*.

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*F. C. Buhl, Technical Representative, Hercules Powder Co., 910 Market Street, Wilmington 99, Delaware. Information concerning Reten 205. Private Communication. May 14, 1964.

LABORATORY APPROACH

If Eq. 1 is used to compute the zeta potential of a filter cake, the combined resistivity of the filter cake must be known. The term $\frac{1}{R} + \frac{4\lambda_s}{\phi}$ in Eq. 1 is the reciprocal of the combined resistivity of the filter cake and the filtrate. An attempt to determine this combined resistivity was made by measuring the resistance across the filter cake during a test run. The resistance was measured using a volt-ohm-microammeter (Simpson, MODEL 269, Simpson Electric Co.) which applies a direct current to the circuit being tested. Difficulty was encountered when making the resistance determinations due to the electrodes in the filter becoming polarized. After a resistance measurement was made, the measured streaming potential varied for a considerable length of time.

Since the combined resistivity across the filter cake was not measured, a graphical technique was used to determine the zeta potential. The graphical technique makes use of an approximate zeta potential ζ_a, computed from the following:

$$\zeta_a = \frac{4\pi k E \eta}{D P R} \qquad (6)$$

Equation 6 can be recognized as Eq. 1 with the effect of surface conductance omitted. The variables in Eq. 6 are readily determined with the apparatus used, as explained in Appendix A.

A relation between the approximate zeta potential, ζ_a, and the zeta potential, ζ, in Eq. 1 can be derived by dividing Eq. 6 into Eq. 1. The following equation will result:

$$\frac{1}{\zeta_a} = \frac{1}{\zeta} + \frac{4\lambda_s}{\zeta\phi} R \qquad (7)$$

If the quantities $\frac{1}{\zeta}$ and $\frac{4\lambda_s}{\zeta\phi}$ are constant over a given range of R, then Eq. 7 is a linear equation relating $\frac{1}{\zeta_a}$ and R. The linearity of this relationship has been demonstrated[15].

In this investigation four or five values of ζ_a were determined for a corresponding number of values of R. The values of $\frac{1}{\zeta_a}$ and R were plotted on arithmetic graph paper from which the values of $\frac{1}{\zeta}$ (the intercept) and $\frac{4\lambda_s}{\zeta\phi}$ (the slope) were determined (Fig. 4).

Values of ζ_a and R were obtained by operating the pressure filter permeameter apparatus in a closed circuit fashion, returning the waste water leaving the system to the supply tank. Initially a value of ζ_a was determined for a filtrate resistivity of three to four thousand ohm meters. Next, sodium chloride was added to the supply tank to lower the resistivity of the water being filtered. The ζ_a corresponding to the lower resistivity was then determined. From the data compiled, values of $\frac{1}{\zeta a}$ and R were plotted (Fig. 4). This technique was used throughout this investigation to obtain values for the zeta potential of coated diatomite filter cakes.

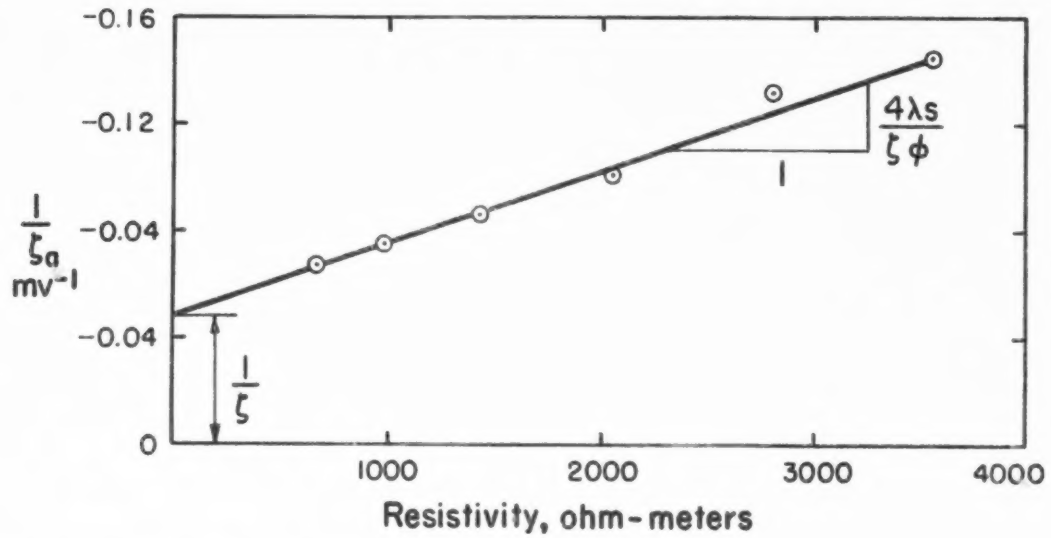

Fig. 4. Reciprocal apparent zeta potential, $\frac{1}{\zeta a}$, as a function of resistivity (Run 67, with 0.000152 lb Polyelectrolyte A per lb Celite 545)

The water used in all of the tests was prepared initially by distillation in a Barnstead still. The distilled water was then passed through ion exchange columns (Amberlite IRA-410, and Amberlite IR-120 resins manufactured by Rohm and Haas Co.) and was stored until used in aged glass containers. The resistivity* of the demineralized water was normally in the neighborhood of 15,000 to 20,000 ohm meters.

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*Resistivity is an electrical property of a uniform conductor and is the resistance of a cube 1 meter on an edge. The units are ohm (meters)^2/meter or simply ohm meters.

Dilute solutions of hydrochloric acid and sodium hydroxide were used to vary the pH of the water supply for the investigations into the effect of pH on the zeta potential of a coated diatomite filter cake. Addition of either of these compounds to the initial water supply lowered the resistivity of the water somewhat. In one instance, where the pH of the water was raised to about 9.4 by adding NaOH, the resistivity of the initial water supply was lowered to about 600 ohm meters.

TEST RESULTS

All pertinent data and some calculated results from the runs made in this study are in Tables 1 and 2. The runs are numbered in the order that they were made. The subscripts attached to polyelectrolyte B indicate the different stock solutions that were used.

A few exploratory runs were made to evaluate an alternative method of coating the diatomite filter media. This consisted of recycling a solution of polyelectrolyte through a formed filter cake. The method was dropped, and the data from these runs have been omitted. Other runs not shown were made to determine the approximate amounts of polyelectrolytes needed to reduce the zeta potential of Celite 545 filter cakes to the iso-electric point.

Uncoated Celite 545

A series of runs was made at the beginning of the study to determine the zeta potential of Celite 545. A zeta potential of -55.3 mv was determined by linear regression using the method of least squares (Fig. 5). The value for zeta potential and the slope of the $\frac{1}{\zeta_a}$ vs R curve agree with previous published results for Celite 545[15].

Polyelectrolyte A

The zeta potential of Celite 545 was changed from -55.3 mv to +49 mv when 0.001 lb polyelectrolyte A per lb of Celite 545 was used to coat the diatomite (Fig. 6). Concentrations up to 0.0133 lb polyelectrolyte A per lb Celite 545 were evaluated. Using amounts of polyelectrolyte A greater than 0.001 lb per lb Celite 545 produced no significant increase in the zeta potential.

Coating Celite 545 with polyelectrolyte A resulted in no significant increase in the impermeability coefficient of the filter cake (Table 1). Polyelectrolyte A is, therefore, a coating material which will reverse the zeta potential of Celite 545 substantially without causing a change in the permeability of the filter cake.

Polyelectrolyte A was reasonably stable when stored as an aqueous solution containing less than one gram per liter. This was established

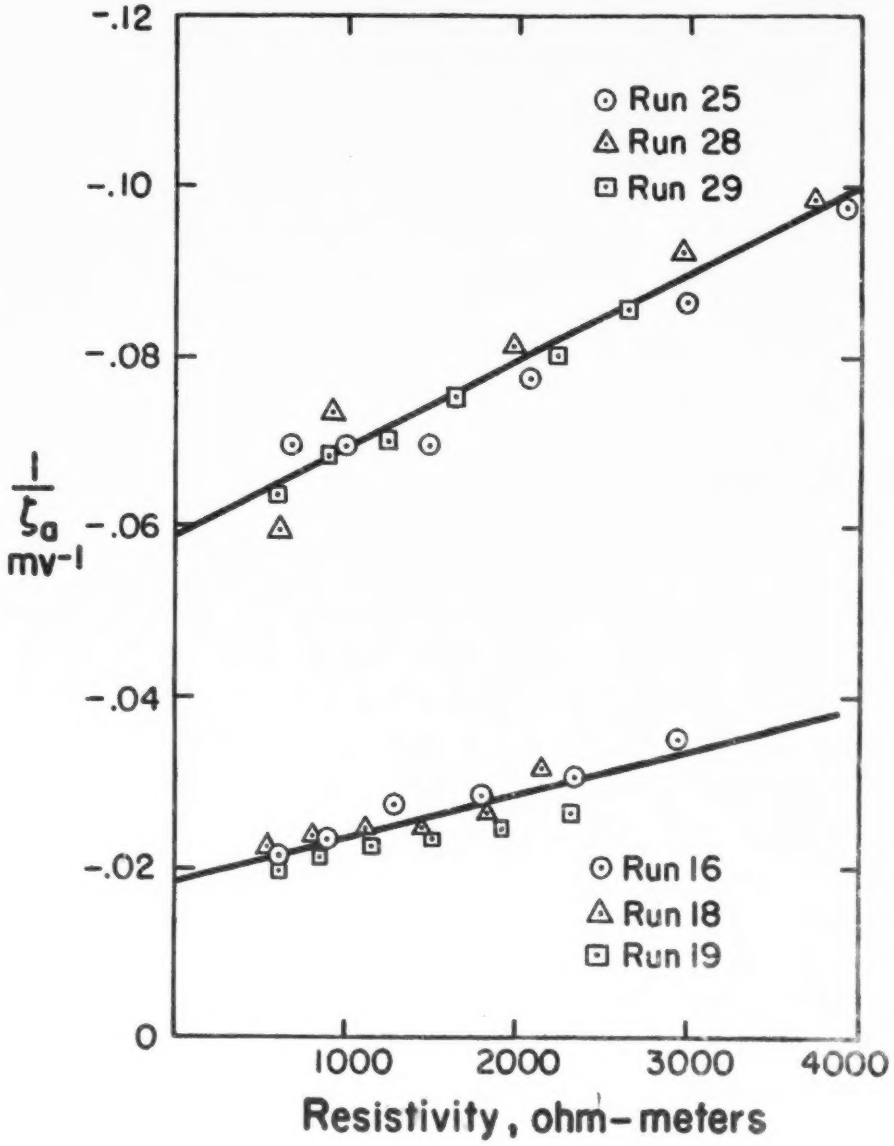

Fig. 5. Reciprocal apparent zeta potential as a function of resistivity Runs 16, 18, and 19 are for uncoated Celite 545. Runs 25, 28, and 29 are for 0.000534 lb Polyelectrolyte C per lb Celite 545.

Table 1. Test data and results for the runs where various amounts of polyelectrolyte were used to coat Celite 545

Run	Polyelectrolyte	$\frac{\text{lb Polyelectrolyte}}{\text{lb Celite 545}}$	K_3 $\frac{ft^5}{\text{gpm lb}}$ [a]		Average ζa	ζ	$\frac{4\lambda s}{\zeta\varphi}(10^6)$
			Beginning of Run	End of Run	mv	mv	(mv ohm meters)$^{-1}$
16	--	--	.76	.79	--	-55.5	5.80
17	--	--	.81	.83	-28.6	--	0
18	--	--	.77	.81	--	-50.0	5.10
19	--	--	.70	.74	--	-55.5	3.40
13	C	.00801	3.17	2.94	- 5.47	--	0
14	C	.00801	3.23	2.65	- 5.89	--	0
15	C	.00801	3.36	2.87	- 3.38	--	0
64	C	.00400	2.92	1.85	- 4.50	--	0
65	C	.00400	1.99	1.57	- 3.97	--	0
22	C	.00133	2.02	1.69	- 6.33	--	8.33
23	C	.00133	2.03	1.66	- 6.66	--	10.00
24	C	.00133	2.07	1.73	- 6.00	--	6.66
83	C	.00100	1.17	1.05	- 5.73	- 6.67	6.66
84	C	.00100	1.39	1.22	- 6.26	- 7.15	6.66
25	C	.000534	1.04	.96	--	-16.4	8.30
28	C	.000534	1.00	.89	--	-17.0	11.00
29	C	.000534	1.00	.92	--	-17.6	10.75
26	C	.000267	.93	.87	--	-33.3	6.66
27	C	.000267	.85	.77	--	-32.8	5.55
30	C	.000267	.88	.85	--	-29.4	5.50
82	C	.000100	.64	.65	--	-37.6	13.0
45	A	.0134	.75	.76	+42.6	--	0
44	A	.00892	.80	.80	+42.9	--	0

[a] K_3 at 20.3°C.

Table 1. (Continued)

Run	Polyelectrolyte	$\frac{\text{lb Polyelectrolyte}}{\text{lb Celite 545}}$	K_3 $\frac{ft^5}{gpm\ lb}$ [a] Beginning of Run	End of Run	Average ζ_a mv	ζ mv	$\frac{4\lambda s}{\zeta\psi}(10^6)$ (mv ohm meters)$^{-1}$
43	A	.00400	.76	.78	+52.3	--	0
42	A	.00200	.83	.80	+51.7	+61.0	1.8
46	A	.00200	.82	.81	+48.7	+52.7	0.8
47	A	.00200	.81	.83	+49.0	--	0
41	A	.00160	.83	.80	+49.5	+59.3	2.0
40	A	.00120	.79	.86	+49.0	+54.0	1.8
39	A	.000802	.76	.75	+49.5	--	0
66	A	.000607	.72	.72	+39.7	--	0
36	A	.000446	.72	.73	+21.9	--	0
37	A	.000268	.84	.84	- 8.9	--	0
38	A	.000268	.69	.73	+ 6.7	--	0
68	A	.000200	.74	.79	0	--	0
67	A	.000152	.77	.78	-10.6	-25.0	35.7
50	B_1	.00594	.72	.71	+23.4	--	0
49	B_1	.00396	.79	.78	+ 3	--	0
48	B_1	.00198	.55	.58	-17.9	--	0
52	B_2	.00600	5.33	2.28	+26.3	+29.2	2.6
53	B_3	.00600	4.03	1.84	+27.2	--	0
54	B_4	.00800	1.51	1.04	-28.2	-33.4	3.5
55	B_4	.00400	.94	.76	-32.6	-42.8	4.1
63	B_5	.00800	9.33	3.71	+29.6	+41.7	6.7
61	B_5	.00600	9.39	--	--	--	--
59	B_5	.00400	5.32	1.98	+29.8	+33.3	2.5
60	B_5	.00300	2.31	1.29	+34.1	--	0
62	B_5	.00250	.99	.85	+20.4	--	0
56	B_5	.00200	.74	.74	+ 5.0	--	0
57	B_5	.00100	.74	.75	+ 4.5	--	0
58	B_5	.00050	.72	.75	-25.2	-29.6	3.3

Table 2. Test data and results for the runs where pH of the water being filtered was varied (0.001 lb polyelectrolyte A per lb Celite 545)

Run	Filtrate pH	Average[a] K_3 $\frac{ft^5}{gpm\ lb}$	Average ζa mv	ζ mv	$\frac{4\lambda_s}{\zeta\psi}$ (10^6) $(mv\ ohm\ meters)^{-1}$	λ_s (10^9) $(ohms)^{-1}$
75	4.82	.73	+47.5	+65.2	13.6	2.52
74	5.74	.71	+47.3	+66.7	7.82	2.74
73	5.99	.70	+44.1	+62.5	6.25	2.05
72	6.40	.69	+41.3	+55.0	3.20	0.93
80	6.95	.78	+46.2	+52.1	1.30	0.35
76	7.42	.74	+39.4	+40.4	.58	0.12
79	7.61	.68	+33.3	+43.5	4.73	1.08
70	7.92	.75	+21.5	+49.0	13.45	3.46
77	8.22	--	0	0	--	--
81	8.70	--	- 2.3	- 2.3	0	0
69	8.91	.81	- 8.86	- 5.9	-50	-1.55
71	8.98	.73	- 5.6	- 3.7	-100	-1.94
78	9.38	.70	-20.7	-14.8	-100	-7.77

[a] K_3 at 20.3°C.

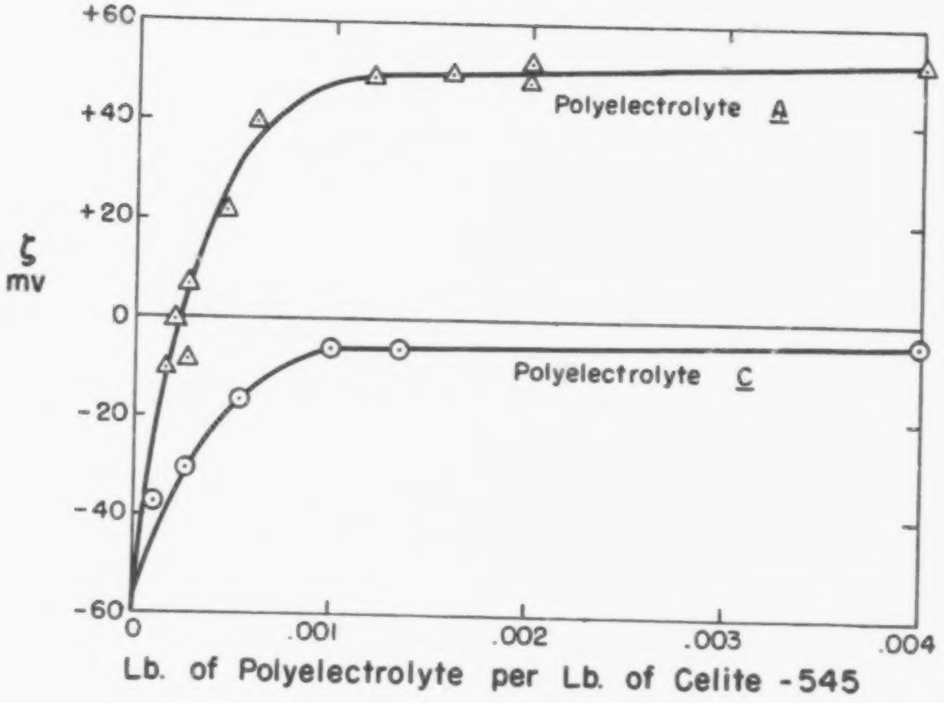

Fig. 6. Zeta potential as a function of the amount of polyelectrolyte used to coat Celite 545

by using newly prepared solutions in some runs and solutions that were over six months old in others. Variations in zeta potential of coated diatomite filter cakes were insignificant when similar concentrations of old or new solutions were used.

Polyelectrolyte B

Reproducible results were not obtained with polyelectrolyte B. Five different stock solutions were used, and they resulted in three different relationships between zeta potential and the amount of polyelectrolyte B used in coating the diatomite. These three different relationships are shown in Fig. 7 as curves $B_{1,2,3}$, B_4, and B_5, where the subscripts indicate the different stock solutions used. The concentrations of all five stock solutions were about the same: approximately 0.1 gram per liter. Stock solution B_5 caused a reversal in the zeta potential of the Celite 545 filter cake. Stock solution B_4 reduced the zeta potential only slightly.

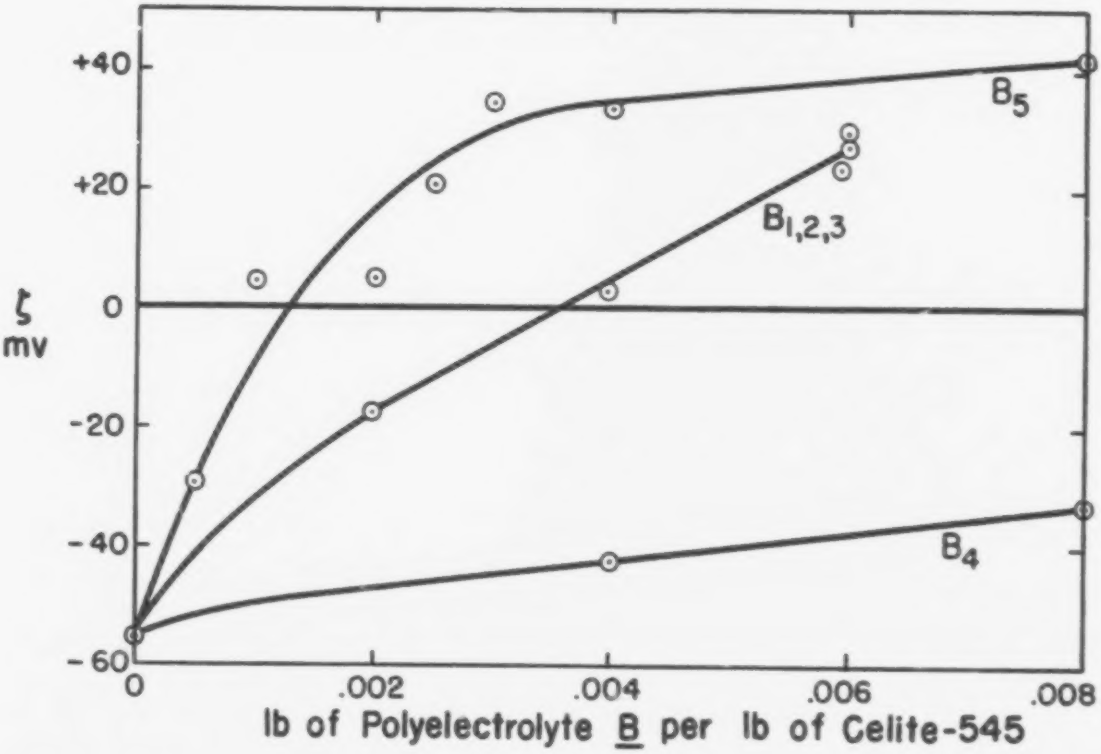

Fig. 7. Zeta potential as a function of the amount of polyelectrolyte B used to coat Celite 545

Coatings of polyelectrolyte B affected the impermeability coefficient of the filter cakes, but the results were inconsistent. Stock solutions B_1 and B_4 caused only slight increases in K_3 for concentrations in excess of 0.006 lb polyelectrolyte B per lb Celite 545, but stock solution B_5 caused a 12-fold increase in K_3 for a like concentration.

Polyelectrolyte C

Polyelectrolyte C lowered the zeta potential of Celite 545 filter cakes but did not reverse it (Fig. 6). Concentrations of polyelectrolyte C in excess of 0.001 lb polyelectrolyte C̲ per lb Celite 545 changed the zeta potential of Celite 545 from -55.3 mv to about -5 mv.

Coating Celite 545 with polyelectrolyte C̲ increased the impermeability coefficient, K_3, of the filter cakes. When enough polyelectrolyte C̲ was used to cause the maximum change in zeta potential, the impermeability coefficient of the filter cake was about twice as high as that for filter cakes prepared with uncoated Celite 545. Further increases in the amount of polyelectrolyte C̲ used for coating produced additional increases in the impermeability coefficient of the filter cake. For the range between 0.0005 and 0.002 lb polyelectrolyte C̲ per lb Celite 545, small changes in the amount of polyelectrolyte C̲ used resulted in large changes in impermeability coefficient (Fig. 8).

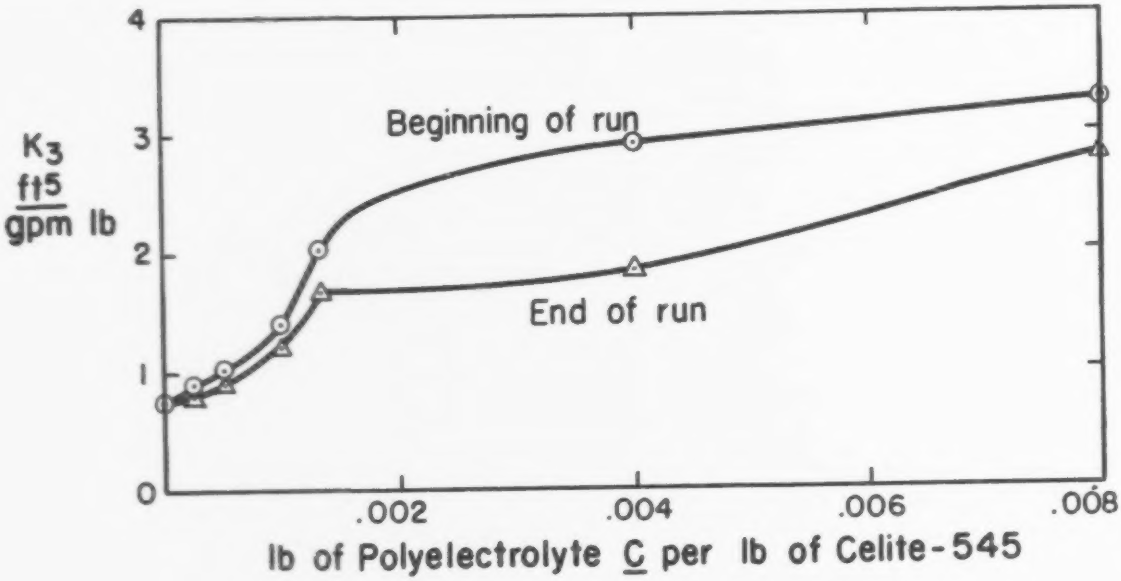

Fig. 8. Effect of polyelectrolyte C̲ on K_3, the impermeability coefficient of Celite 545

Solutions containing less than one gram per liter of polyelectrolyte C̲ were somewhat difficult to prepare. It was necessary to mix the solutions with a magnetic stirrer for more than two hours to obtain a clear, particle-free solution. The stock solutions that were prepared, however, were reasonably stable, and similar test results were obtained with both old and new stock solutions.

Statistical Analysis of Data

A statistical analysis was made to determine the variability of the test data and the effect of the variability of the data on the calculated values of zeta potential[19]. Statistical analyses of five sets of data were made, with three runs in each set (Table 3).

The correlation coefficient is a measure of the scatter of bivariate data, with a value of plus or minus one indicating that all data points fall on a straight line when plotted on arithmetic graph paper. A value of zero indicates no relationship between two variables. The correlation coefficients for the runs investigated indicated that the scattering of test data was not excessive. The plotted data for two sets of data are shown in Fig. 5.

The 95% confidence intervals of the zeta potentials (Table 3) are about plus or minus 10%. The small amount of variation in the data ($\frac{1}{\zeta_a}$ and $\frac{4\lambda_s}{\zeta\phi}$) and the small confidence intervals for zeta potentials at the 95% level of significance indicated that the laboratory testing technique was satisfactory.

Effect of pH on Zeta Potential

Since polyelectrolyte A is reported as being a polyamine, the cationic charge characteristic of the amine groups should be eliminated at high pH values; however, it would probably not be reversed in sign. A series of runs (69 through 81) was made to verify the pH dependence of the zeta potential. The average zeta potential of Celite 545 coated with 0.001 lb polyelectrolyte A per lb Celite 545 decreased as the pH of the water being filtered was increased above a pH of seven (Fig. 9); at pH values above 8.7 the zeta potential was negative in sign. This would indicate that functional groups other than amines are probably present in the polyelectrolyte molecule. No significant change in the impermeability coefficient was observed for different pH values (Table 2).

Table 3. Statistical analysis of test data

Run Number	Polyelectrolyte Used	$\frac{\text{lb Polyelectrolyte}}{\text{lb Celite 545}}$	Equation[a] for $\frac{1}{\zeta a}$ $(\frac{1}{\zeta} + \frac{4\lambda_s}{\zeta\varphi} R)$	Standard Deviation of $\frac{1}{\zeta a}$ $(mv)^{-1}$	Standard Deviation of Slope $\frac{4\lambda_s}{\zeta\varphi}$ $(mv\ ohm\ meters)^{-1}$	Zeta Potential ζ (mv)	95 % Confidence Interval for ζ (mv)	Correlation Coefficient
16, 18, 19	---	---	$0.0181+(5.03\times10^{-6})R$	0.0014	0.568×10^{-6}	-55.3	-51.6 to -61.1	.92
22, 23, 24	e	.00133	$0.159+(8.03\times10^{-6})R$	0.012	2.70×10^{-6}	- 6.29	- 5.85 to - 6.71	.59
25, 28, 29	C	.000534	$0.059+(10.13\times10^{-6})R$	0.0028	0.650×10^{-6}	-17.0	-16.3 to -17.7	.97
26, 27, 30	C	.000267	$0.0326+(5.55\times10^{-6})R$	0.0027	0.723×10^{-6}	-30.7	-28.3 to -33.3	.89
42, 46, 47	A	.00200	$0.0186+(0.805\times10^{-6})R$	0.0009	0.237×10^{-6}	+53.5	+51.0 to +56.2	.69

[a] Determined by linear regression using least squares method for $\frac{1}{\zeta a}$ on R.

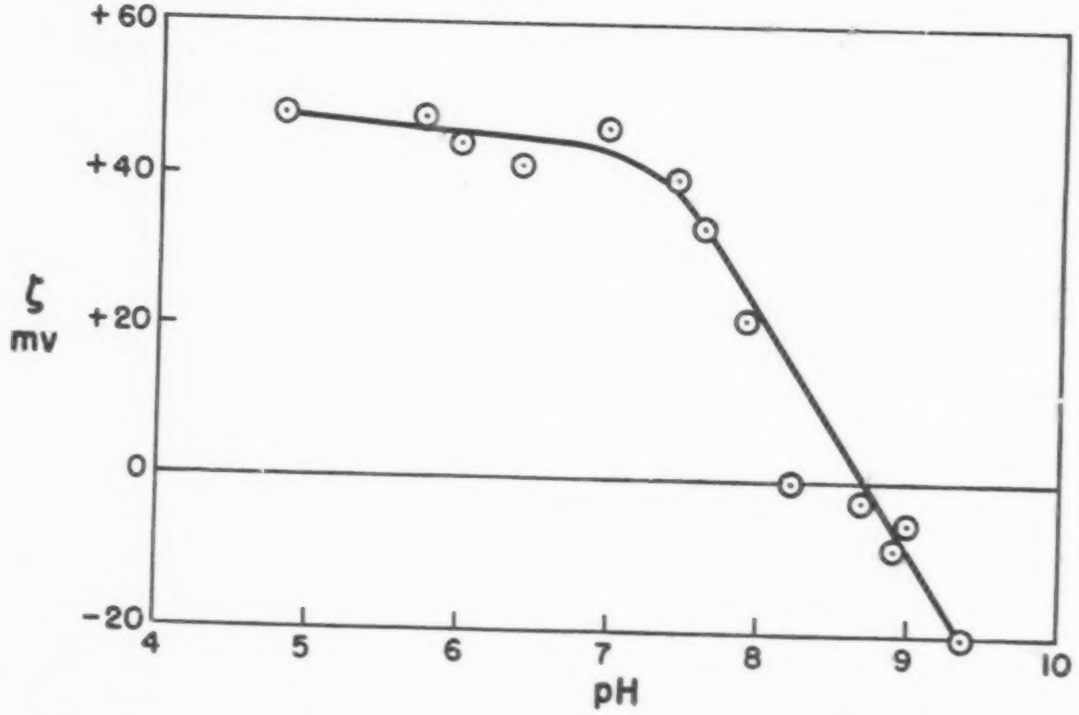

Fig. 9. Effect of pH of the water being filtered on the average apparent zeta potential of Celite 545 coated with 0.00100 lb Polyelectrolyte A per lb Celite 545

Specific Surface Conductance

In the graphical method used to compute zeta potential, ζ, the slope of the curve (Fig. 4) is directly proportional to the specific surface conductance, λ_s, of the filter media. From the values of the slopes, $\frac{4\lambda_s}{\zeta\phi}$ (Table 1), values of specific surface conductance were computed. The value of mean particle size, ϕ, was taken to be 21×10^{-6} meters[7]. The specific surface conductance of uncoated Celite 545 was computed as 1.42×10^{-9} ohm^{-1}. A value of 1.77×10^{-9} ohm^{-1} was computed from data presented elsewhere[15].

At a pH of about 6.9 the specific surface conductance of Celite 545 coated with various amounts of polyelectrolyte A appeared to be zero (Table 1). Exceptions to this general trend were found in Runs 42, 46, and 47, where λ_s was found to be 0.22×10^{-9} ohm^{-1}. In the runs where the pH of the water being filtered was varied and Celite 545 was coated with 0.001 lb polyelectrolyte A per lb Celite 545, the calculated values for the specific surface conductance decreased from 2.5×10^{-9} ohm^{-1} at a pH of 4.8 to a value of zero as the pH approached 8.0 (Table 2). Above pH values of 8.9 the values of λ_s were negative in sign. The slopes for pH values below 6.0 and above 8.9 were not very reliable because the range of resistivities over which measurements were made was only a few hundred ohm meters. For example, in Run 75 hydrochloric acid was added to the water supply to lower the pH to about 4.8. The addition of this electrolyte caused a decrease in the resistivity of the water supply to about 590 ohm meters. The lowest resistivity at which measurements were made was about 240 ohm meters, so the range was only 310 ohm meters. In the runs where no acid or base was added, to change the pH of the water being filtered, the range of resistivities at which measurements were made was normally about 2,000-3,000 ohm meters (Fig. 4).

The specific surface conductance of Celite 545 coated with polyelectrolyte B indicated no general trend. When using stock solutions B_1 and B_3 to coat the Celite 545 the values of λ_s were zero. When using stock solutions B_2 and B_4, values of λ_s ranged from 0.40 to 0.90×10^{-9} ohm^{-1}. In about half the runs where stock solution B_5 was used, λ_s was zero, but values of λ_s in the other half ranged from 0.4 to 1.2×10^{-9} ohm^{-1}.

The specific surface conductance of Celite 545 coated with polyelectrolyte C decreased as the amount of coating material used was increased. The calculated values of λ_s ranged from about 0.9×10^{-9} ohm^{-1} at concentrations of 0.000267 lb polyelectrolyte C per lb Celite 545 to zero at 0.004 and 0.008 lb polyelectrolyte C per lb Celite 545.

In general all three coating materials cause λ_s to be lower than for uncoated Celite 545.

Summary of Test Results

Polyelectrolyte A produced a substantial reversal in the zeta potential of Celite 545 filter cakes without significantly changing the hydraulic characteristics of the filter cake. However, the zeta potential of the filter cake coated with 0.001 lb polyelectrolyte A per lb Celite 545 depended on the pH of the water being filtered. Above a pH of 8.7 the positive charge characteristic of the coating was eliminated.

Polyelectrolyte B caused reversals in zeta potential in some tests, but only slight changes in others. At concentrations of polyelectrolytes B_5 and $B_{1, 2, 3}$ above 0.0060 lb per lb Celite 545, the zeta potential reversed its sign, but the impermeability of the filter cake increased more than seven-fold.

Polyelectrolyte C reduced the zeta potential of a Celite 545 filter cake to within about 5 mv of the iso-electric point but did not reverse the sign. This reduction in zeta potential was accompanied by an increase in the impermeability coefficient of the filter cake. The tests using polyelectrolyte C were all made at pH of about 6.9. It is possible that at some other pH, possibly lower, polyelectrolyte C would reverse the zeta potential.

The specific surface conductance of Celite 545 coated with any of the three polyelectrolytes studied differed from that of uncoated Celite 545. These coating materials caused a reduction in the specific surface conductance, sometimes to zero.

INTERPRETATIONS AND DISCUSSION

Interpretations

Two probably interrelated phenomena were observed in this study. First, there were concentrations of polyelectrolytes A, B_5, and C above which no significant additional changes in zeta potential were observed (Figs. 6 and 7). Second, for concentrations of polyelectrolytes B_5 and C greater than that needed to produce the maximum change in zeta potential, the impermeability coefficient, K_3, decreased between the beginning and the end of the test runs (Table 1 and Fig. 8). Polyelectrolyte A showed no decrease in K_3.

The first phenomenon might be explained on the basis of the surface area available for coating. When enough polyelectrolyte is used to coat all the area with a mono-molecular layer the charge characteristic of the coating material should be predominate over the charge characteristic of the coated material. If additional coating material builds up on the coated material little change in surface charge characteristic would be expected. Another possible explanation might be that only so many polymer molecules can become attached to the available surface area and any extra molecules will stay in solution. Either explanation could be the reason for observing plateaus in Figs. 6 and 7. The second phenomenon, concerning the decrease of K_3 during a test run, might be explained on the basis of a build up of polymer molecules. If multi-molecular layers of polymers were initially formed due to some polymer-polymer bonding or a concentration effect then it would have been possible for a desorptions process to set in as the test run progressed. Such a desorption process could result from the hydraulic shear forces existing in the filter pores or from the lack of polymer concentrations in the water being filtered causing a concentration gradient effect.

The lack of change in K_3 during test runs where polyelectrolyte A was used indicates that probably only a given number of polymer molecules were adsorbed to the filter surface area regardless of the concentrations of A in the mixing slurry. Conversely, polyelectrolytes B_5 and C probably formed multi-molecular layers when more polymer was used than was needed for covering the available surface area. The excess layers of polymers would have increased the impermeability coefficient of a diatomite filter cake by decreasing the porosity of the individual diatoms. As the test runs progressed some of the excess polymers could have desorbed from the filter surface area, thus decreasing the impermeability coefficient.

The polyelectrolytes studied might have deposited either a few molecular layers or many molecular layers depending on the charge characteristic of the polyelectrolyte molecule. The charge characteristic of the polyelectrolyte molecule is determined by the number of cationic and anionic sites in the molecular structure. If there are more cationic sites than anionic sites, then the polyelectrolyte is called a cationic polyelectrolyte. The three polyelectrolytes used in this study were all called cationic polyelectrolytes, but this does not imply that all three had the same ratio of cationic sites to anionic sites.

In light of the previous discussion concerning increases in K_3 caused by using increased amounts of polyelectrolyte to coat diatomite filter cakes, polyelectrolyte A probably has a much larger number of cationic sites than anionic sites. When enough material was deposited on the surface of the diatomite to give a significant positive charge to the filter media, additional material was not deposited because of a strong electrical repulsion caused by the much larger number of cationic sites. On the other hand it is possible that polyelectrolytes B and C have only a few more cationic sites than anionic sites in their molecular structure. Multi-molecular layers of these polyelectrolytes might have built up if cationic sites of one molecule became attached to the anionic sites of adjacent molecules.

It is impossible to explain why polyelectrolyte A differs from polyelectrolyte C in changing the zeta potential of Celite 545 without knowing more about the chemical and physical properties of these two compounds. This information was not divulged in correspondence with the manufacturers of these products. The manufacturer of polyelectrolyte C did indicate, however, that the cationic sites per molecular weight ratio was 1:1600 and that the molecular weight was in excess of one million. Had similar information been made available for polyelectrolyte A the cationic sites to molecular weight ratio would probably have been reported much higher. This would be consistent with the fact that polyelectrolyte A changed the zeta potential of Celite 545 about 100 mv, but polyelectrolyte C changed the zeta potential only about 50 mv.

The above discussions concerning the charge characteristics of the polyelectrolytes used in this study are speculative, because other important variables such as pH, type of ionic sites, and branching of the molecule were not considered.

Discussion

The purposes of this investigation was to determine the zeta potential and impermeability coefficient of diatomite filter media coated with various amounts of cationic organic polyelectrolytes. In a broader sense the purpose was to determine whether any commercially available cationic polyelectrolytes would change the normally negative zeta potential of diatomite to a positive value without materially decreasing the permeability.

The tests conducted were quite restrictive in that only one grade of diatomite was used and only three available coating materials were evaluated. The significance of the test results lies in the fact that one coating material, polyelectrolyte A, produced a substantial reversal of zeta potential of Celite 545 with no significant decrease in permeability.

Coating diatomite with polyelectrolyte A should increase the removal of bacteria, color, and turbidity in diatomite filtration of surface water. If it does, designers of diatomite filter plants can specify grades of coated diatomite that are much coarser than the grades of plain diatomite currently being used. A decrease in filtration costs will result if the savings in pumping costs is greater than the cost of coating the diatomite.

Another use for diatomite with electropositive coatings would be in filter plants where variations in raw water quality make increased removal efficiencies necessary during certain periods to maintain a satisfactory finished water.

In diatomite filtration the use of electropositive coating materials would require only minor changes in regular plant facilities. Mixing of polyelectrolytes and diatomite could be accomplished in slurry mix tanks. The process of coating the precoat diatomite might require additional equipment (for example, a small slurry mixing device) at the point where the precoat diatomite is brought into the system.

The use of polyelectrolytes for coating rapid sand filter media is a much different problem than that of coating diatomite. When using polyelectrolytes as filter conditioners a polyelectrolyte is fed continuously at a point in the treatment process just ahead of the filters. No one has determined whether polyelectrolytes function by producing tough floc, which deposits in layers in the filter and withstands the shear forces that tend to dislodge the floc, or whether they coat the filter media and provide a surface active agent which adsorbs floc particles. Until the basic function is determined, the best way of using polyelectrolytes in rapid sand filtration can not be specified.

The use of polyelectrolytes in the treatment of potable water supplies has been restricted by several factors. Many polyelectrolytes have been produced for use in solids-liquid separation operations, but only a few have been approved by the Public Health Service for use in treating public water supplies. Polyelectrolyte A is not one of the approved materials. As more investigations are made, using polyelectrolytes as filter conditioners and coagulant aids, the approval or disapproval of the many available compounds should come about more quickly.

Another restrictive factor is a lack of information about the chemical and physical properties of polyelectrolytes. It is difficult to compare these materials or even to use them effectively without knowing what they are or why they function as they do. For example, some cationic polyelectrolytes react unfavorably with chlorine[17]. The details of reactions such as this should be studied and understood before cationic polyelectrolytes are recommended for use in the filtration phase of water treatment. Part of the lack of information results from manufacturers who are not willing, or are unable, to make known information concerning their products. Further, most investigators do not have the facilities or means for making complicated analysis of the polyelectrolytes that they are using.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The results of this investigation have led to the following conclusions:

A. Polyelectrolyte A had several desirable characteristics when used to coat Celite 545.

  1. The zeta potential of Celite 545 was reversed from -55.3 mv to +49 mv when at least 0.001 lb polyelectrolyte A per lb Celite 545 was used to coat the diatomite at a pH of 6.9.
  2. No significant increase in impermeability coefficient was observed for concentrations up to 0.0133 lb polyelectrolyte A per lb Celite 545.
  3. At concentrations of two grams per liter and less, polyelectrolyte A was easy to dissolve and was stable. Stock solutions several months old did not lose their ability to reverse the zeta potential of Celite 545.

  It was observed, however, that at pH values greater than about 8.5, the zeta potential of Celite 545 coated with 0.001 lb polyelectrolyte A per lb Celite 545 was near the iso-electric point, and at higher pHs the zeta potential was negative.

B. Polyelectrolyte B had undesirable characteristics as a coating material.

  1. Different stock solutions produced widely varying values of zeta potential of Celite 545 at similar coating concentrations.
  2. At high concentrations (about 0.006 lb polyelectrolyte B per lb Celite 545) the impermeability coefficient of the filter cakes was greatly increased.
  3. When stored in a small, capped, glass bottle on the laboratory shelf, polyelectrolyte B appeared to be hygroscopic.

C. Polyelectrolyte C might be potentially useful as a coating material.

  1. Using concentrations greater than 0.001 lb polyelectrolyte C per lb Celite 545 the zeta potential of Celite 545 was reduced from -55.3 mv to about -5 mv.
  2. At a concentration of 0.001 lb polyelectrolyte C per lb Celite 545 the impermeability coefficient of a Celite 545

filter cake was about doubled, and at higher concentrations the impermeability coefficient was quadrupled.

D. Zeta potentials and impermeability coefficients can be determined using the pressure filter permeameter and recording potentiometer described in Appendix A. The results obtained with this apparatus are reproducible.

E. Information about commercially available cationic polyelectrolytes is not sufficient for determining why different polyelectrolytes produce different results when used in similar tests.

Recommendations

As a result of this investigation several recommendations are made:

A. The removal efficiencies of particulate matter on filter media coated with polyelectrolytes should be determined by laboratory and field tests. The effect of zeta potential of a filter media on the removal of various kinds of particulate matter by filtration should be also determined.

B. The effect of other polyelectrolytes on the zeta potential and permeability of diatomite filter media should be determined.

C. A method should be developed for measuring the combined resistance of a filter cake in the pressure filter permeameter. If this were done, only one set of data would be required to determine the zeta potential instead of the four or five sets of data needed in these investigations.

D. Chemical and physical analysis of the polyelectrolytes used in this and other studies should be made and published as an aid in explaining how polyelectrolytes function as filter conditioners.

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APPENDIX A: DESCRIPTION AND OPERATION OF THE PRESSURE FILTER PERMEAMETER

DESCRIPTION OF THE APPARATUS

Some of the components of the pressure filter permeameter are commercially available, and others are fabricated from clear plexiglass (Fig. 10). The arrangement of these components is shown in the flow diagram (Fig. 11). The components are as follows:

Filter

The filter was built up from plexiglass blocks 1/2 in. thick. The front half of the filter was made by cementing together the front block, the inlet block, and the septum block (Figs. 12 and 13). The adhesive used was a solution of plexiglass chips in chloroform. The back half of the filter was made by cementing the back block to the outlet block. After the two halves had been fabricated the inlet and outlet holes were drilled to receive 1/4 in. copper tubing connectors which were cemented in place with an epoxy resin material (Figs. 13 and 14). Flow entered the filter tangentially, which caused high enough velocities in the filter to keep the diatomite in suspension. The filter septum, a 100 mesh woven wire screen, was supported by cross braces of No. 12 copper wire. One O-ring, 2 1/2 in. by 1/8 in., held the septum in place. Another O-ring, 3 1/4 in. by 1/8 in., formed a seal between the two halves of the filter when it was clamped together (Fig. 14).

Precoat Pot

The precoat pot was clear plexiglass tubing, 1/4 in. thick, 3 in. I. D., and 4 in. long. A 4 1/2 in. by 4 1/2 in. by 1/2 in. plexiglass block cemented to one end served as a bottom and support. A 4 1/2 in. by 4 1/2 in. by 1/2 in. plexiglass block with a 3 in. opening cemented to the other end served as a flanged end for another 4 1/2 in. by 4 1/2 in. by 1/2 in. plexiglass block used as a lid. The lid was grooved for a 3 1/4 in. by 1/8 in. O-ring, and was clamped to the flange by a metal screw clamp (Fig. 10).

An inlet and an outlet were located in the side wall at about one-half

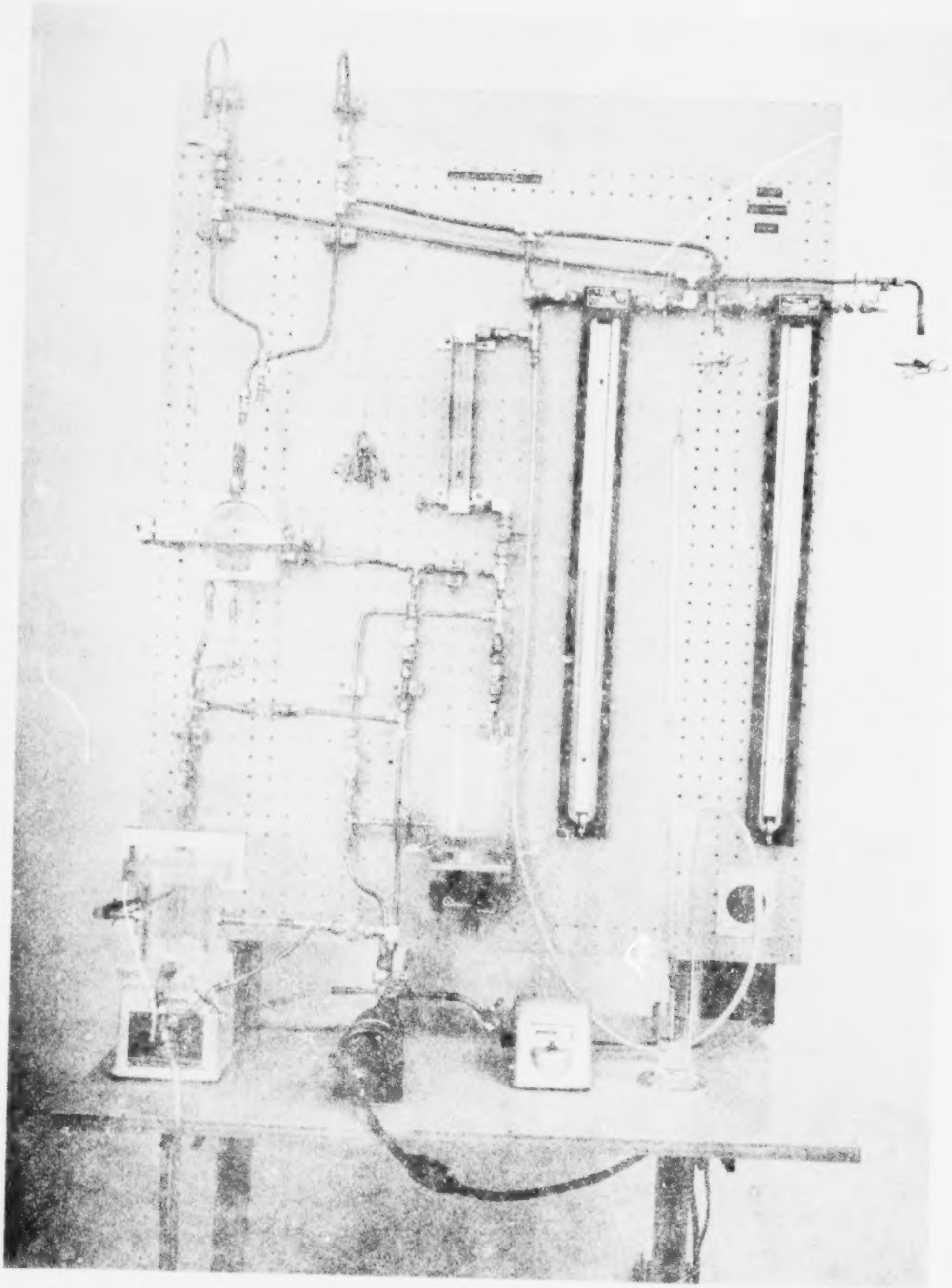


Fig. 16. Pressure filter permeameter

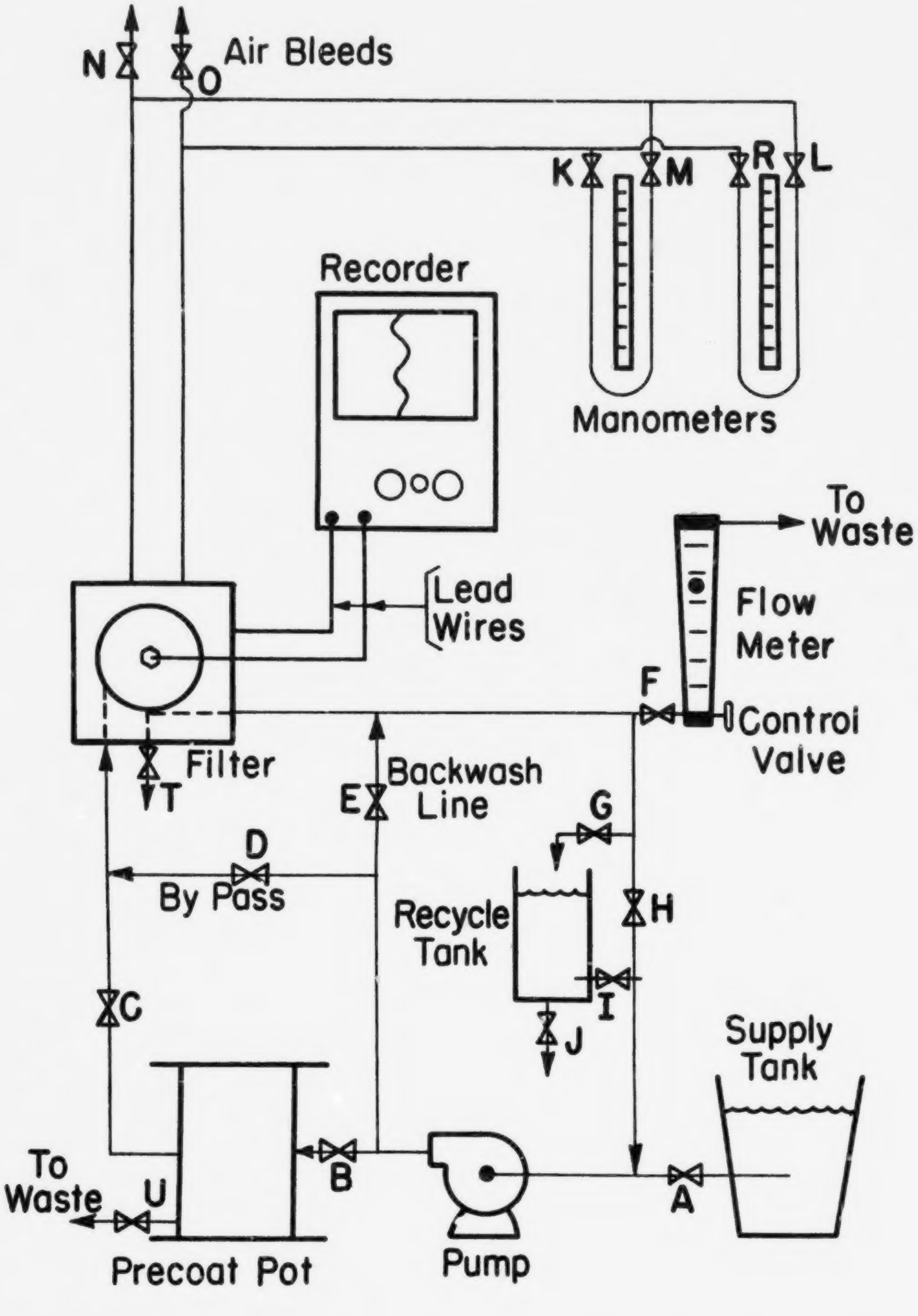


Fig. 11. Flow diagram of pressure filter permeameter

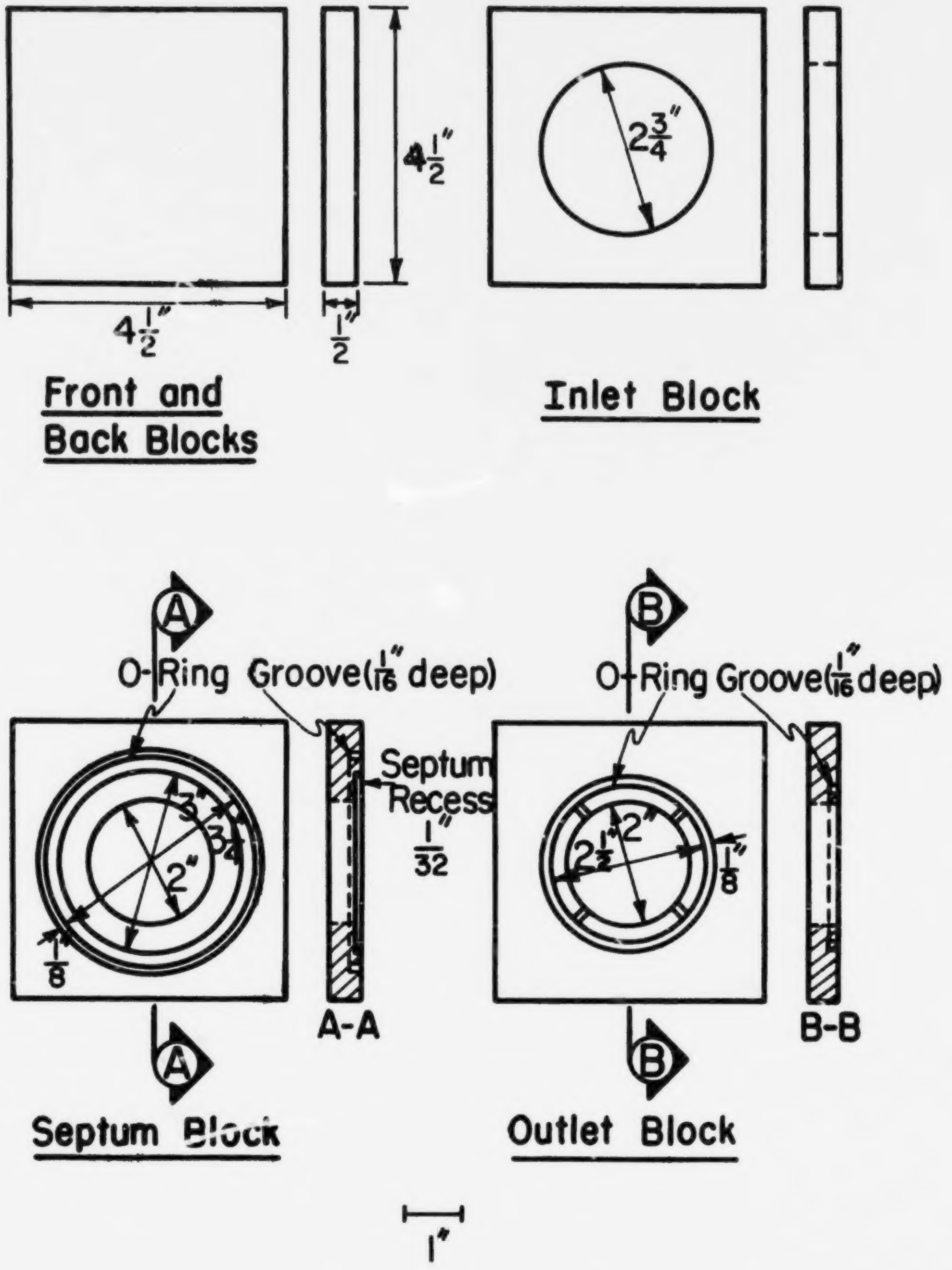
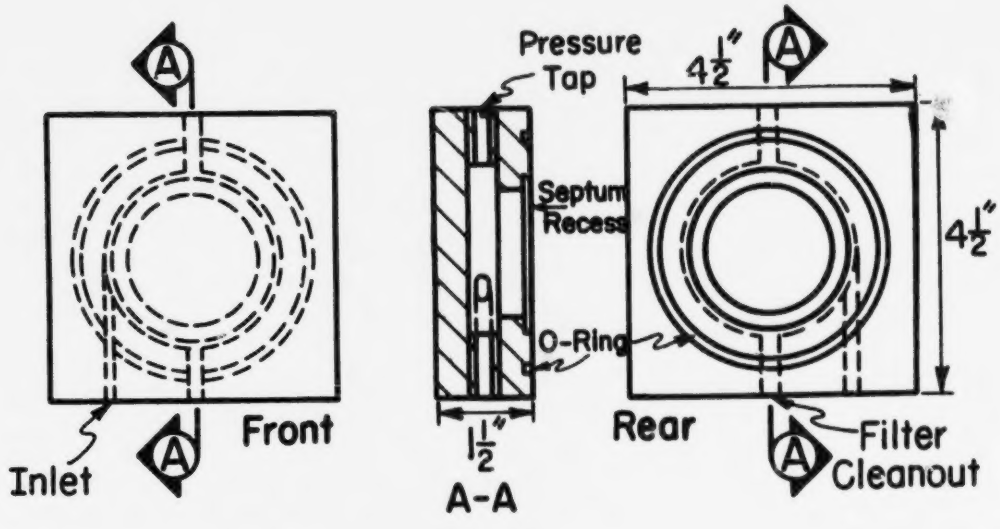
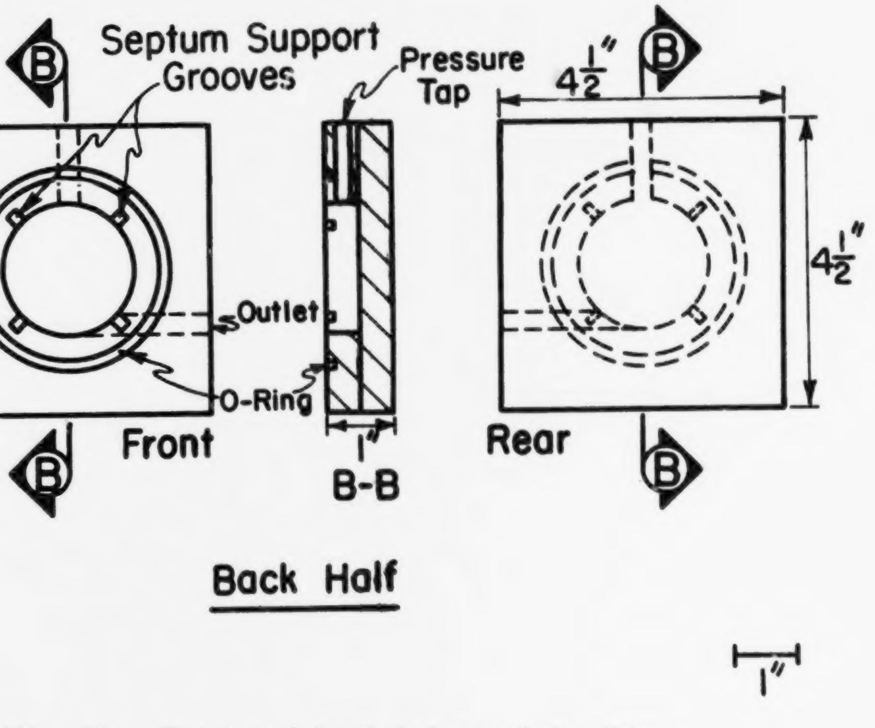


Fig. 12. Filter components



Front Half



Back Half

Fig. 13. Front and back halves of the filter

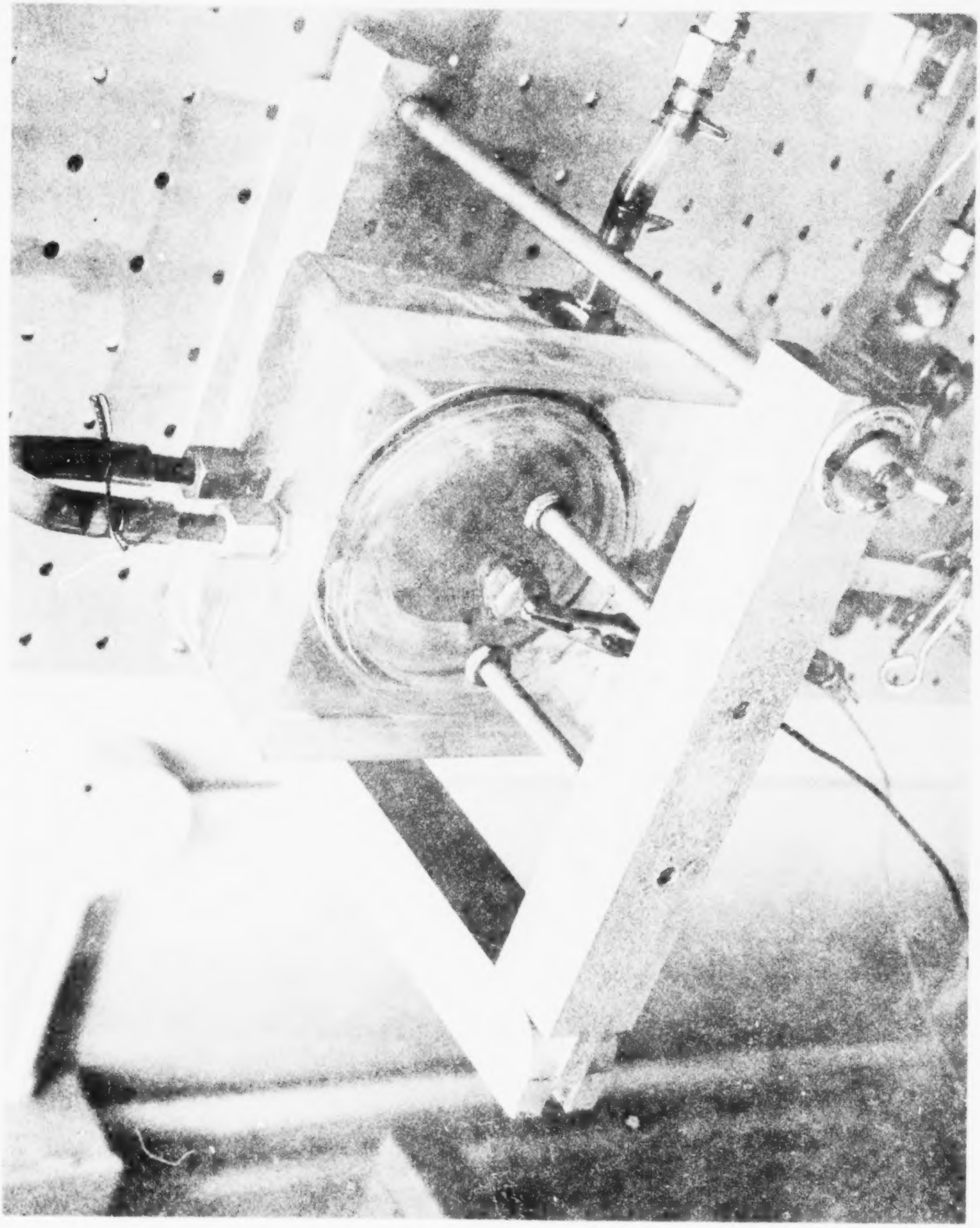


Fig. 14. Assembled filter

the depth of the precoat pot. A drain outlet at the bottom of the precoat pot was used for cleaning and flushing.

The precoat pot was supported on a magnetic stirrer (Magnestir, Catalog No. 52617, Chicago Apparatus Co.). A small magnetic stirring bar placed in the precoat pot kept the diatomite in suspension when the magnetic stirrer was in operation.

Recycle Chamber

The recycle chamber was a clear plexiglass tube, 1/4 in. thick, 3 in. I.D., and 6 in. long. A 4 1/2 in. by 4 1/2 in. by 1/2 in. plexiglass block cemented to one end served as a bottom and support. Flow entered the recycle chamber from the top through a copper tube emptying 1 in. above the chamber. The open top provided a means of introducing any desired material, such as an acid cleaning solution, into water flowing through the system. An outlet was located in the side wall near the bottom and a drain was located in the bottom.

Water Supply Tank

The water supply tank was a 30 liter plastic waste container. Two Tygon tubing lines (1/4 in. I.D.) connected outside of the plastic container by a glass tee siphoned the water from the supply tank and delivered it to the suction side of the pump. Since the water supply tank had no rigid connection to the apparatus, it could be easily removed and cleaned after each run.

Pump

The pump used was a 1/20 horsepower, centrifugal pump (Eastman Industries, Model B-1, Type 100). This pump has a capacity of 7 gpm at zero head and a shut off head of 17 psig.

The normal flows used are less than 1% of the maximum capacity of the pump operating at 110 v. A variable transformer (Standard Electrical Products Co., Type 100BU) reduced the voltage applied to the pump motor thereby reducing the capacity of the pump to a value nearer the range needed.

Flow Meter

The flow rate was determined by a rotameter (Tube size R-2-15-C, Brooks Instrument Co.). The rotameter tube was graduated in percent of maximum flow. Three separate 1/8 in. diameter floats (pyrex glass, stainless steel, and carboloy) provided a continuous flow measuring range from 0.80 cc/sec to 5.60 cc/sec. In terms of surface flow rate this range is from 0.58 gpm/ft^2 to 4.07 gpm/ft^2.

A needle valve at the inlet to the rotameter was used to vary the flow and provide fine adjustment.

Manometers

Two manometers (king Manometer, Model BUB-24, King Engineering Corp.) were used for determining the head loss across the filter cake. One manometer containing a red colored fluid with a specific gravity of 2.94 at 20°C (Indicating Liquid No. 294, part No. 2992, King Engineering Corp.) measured head losses up to 3.82 ft of water. The second manometer containing mercury measured head losses up to 25.9 ft of water.

Piping and Valves

Piping was 1/4 in. O.D. copper tubing with compression fittings for rigid connections, and 1/4 in. I.D. Tygon tubing for flexible connections. No. 18 copper wire was used to secure the connections of Tygon tubing and copper tubing (Fig. 14).

Quarter turn brass valves were used on the copper tubing lines and pinch clamps on the Tygon tubing lines for flow control.

Filter Electrodes

Silver-silver chloride electrodes were used in measuring streaming potentials across the filter cake when water was being filtered. They were not needed for making impermeability measurements of the filter cake. The electrodes were mounted in 1/4 in. brass pipe plugs. Holes were drilled through the center of the front and back blocks and were tapped to receive the brass pipe plugs (Fig. 14).

Recording Potentiometer

Streaming potentials across the filter cake were measured and recorded with a Sargent Recorder (Model MR., Catalog No. 3-72150, E.H. Sargent and Co.). The Sargent Recorder is an automatic, multiple range, variable speed, self balancing potentiometer which graphically records measured potential as a function of time.

Conductivity Bridge

In determining zeta potentials from streaming potential measurements, the electrical resistivity of the water being filtered must be determined. This measurement of resistivity was made with a conductivity bridge (Model RC-16B2, Industrial Instruments Inc.), and a conductivity cell of the Freas type.

To calculate the resistivity of the filtrate from a measured value of resistance, a "cell constant" must be determined using a standard solution of electrolyte, such as KCl, of known resistivity (eg. 0.10 N KCl has a resistivity of 8569 ohm meters at 20°C).

OPERATION OF THE PRESSURE FILTER PERMEAMETER

Various forms of the pressure filter permeameter have been used by other investigators (7, 15).

The apparatus was used originally to determine the zeta potential of various diatomite filter aids by streaming potential measurements. In later investigations the apparatus was used to determine the impermeability coefficients of diatomite filter aids. In this investigation both streaming potential and impermeability measurements were made at the same time.

The following technique was used to determine the impermeability coefficient, K_3, and the zeta potential of the filter cake. The four operations are presented in the time order of an actual determination. Valves which are manipulated during operation of the apparatus are designated by letters in Fig. 11.

Preliminary Operations

The system must first be cleaned of any contaminants, particulate or chemical, which might affect the desired results. The effects of contaminants have been reported[7]. To clean the system a large quantity of clean water or a chemical cleaning solution is passed through the various units and connecting conduits. The clean water, or chemical cleaning solution, can be introduced into the system through the supply tank or the recycle chamber.

When the system is clean the supply tank is filled with the desired quality of water, distilled, deionized, etc. Initially all valves should be closed.

By opening valves A, B, and U the pump is primed by gravity flow. The pump may be turned on to aid in removing any entrapped air. Valves B and U are shut after the pump is primed. The voltage regulator is then adjusted to slow the pump motor to the desired range.

The pump is turned on, and the system is purged of any air trapped in high places in the conduits and filter. This is accomplished by manipulating valves to direct the flow through the system to the various outlets.

When purging the system of air, or when actually making a run, the first valve on the outlet side of the pump (B, D, or E) should be partially closed to dissipate the high energy capacity of the pump which is not needed in normal operations. The final step in the purging operation is to fill the precoat pot to the desired level, normally about two-thirds full.

Precoating Operation

In the precoating operation the diatomite is deposited on the septum to form a filter cake.

A previously weighed amount of diatomite is placed in the precoat pot and the stirring device turned on to keep the diatomite in suspension. The water level in the precoat pot is then brought up to about 1/2 in. from the top, and the lid is clamped on.

Water is then recycled in a closed circuit through the pump and filter by opening valves D and H keeping all other valves closed. Valve D is only partially opened. After a few seconds have elapsed to allow the system to reach flow equilibrium, the flow is diverted through the precoat pot in order to sweep the suspended diatomite up to the filter to be deposited on the septum. The flow is diverted by partially opening valve B, fully opening valve C, and then closing valve D. Now the flow passes through the pump, precoat pot, filter, and back to the pump. The precoat rate is set by adjusting valve B to provide a flow rate just great enough to keep the diatomite from settling in the filter. Recycling is continued until almost all of the diatomite is deposited on the septum. This is normally determined by observing when the water, as it passes through the precoat pot, becomes no clearer.

At this time the precoat of diatomite is observed, and its general appearance is recorded as good or bad. Since flow in the filter inlet chamber is tangential, too high a precoat flow rate will cause a spiral appearance on the surface of the filter cake. If the filter cake is not uniform the diatomite must be removed from the system, and the preliminary and precoating operations repeated.

When the diatomite is deposited on the septum, the precoat pot is bypassed by first opening valve D and then closing valves B and C. Since this apparatus is a pressure filter, a pressure differential across the filter cake must be maintained at all times. This means that before any valve is closed another valve, located to maintain adequate flow through the filter cake, must be opened.

Filtering Operation

The transition from precoating operation to filtering operation is now made. With the control needle valve fully opened, valve A and then valve F are opened. Then by closing valve H the water flows from the supply tank through the pump, filter, rotameter, and to waste. The apparatus is then taking raw water from the supply tank, filtering it, and passing it out of the system.

The next step is to adjust valve D so that flow through the system is a little greater than can be measured by the rotameter. After this coarse adjustment has been made, further variations and fine adjustments of the flow rate are made with the control needle valve.

In measuring head loss, the mercury manometer should be used first if the approximate head loss is not known. To place the mercury manometer in service, valve R is opened and then valve L slowly opened.

For streaming potential measurements, connecting wires from the recording potentiometer are attached to the electrodes on the filter. The potentiometer is then turned on, and the proper adjustments are made for chart speed, damping, range, and stabilization.

The flow rate is set at the highest value possible. This maximum flow rate will be determined by the highest measurable flow rate of the rotameter or the maximum head loss range of the manometer. After the system has reached flow equilibrium (a constant flow rate maintained) the first set of data are observed and recorded. These data are:

1. Flow rate determination
2. Head loss across the filter cake
3. Filtrate temperature
4. Filtrate electrical resistance
5. Electrical potential (automatically recorded, Fig. 15).

The flow rate is then decreased, and the system allowed to reach flow equilibrium. Another set of data are recorded for the lower flow rate. Three or four such sets of data are determined.

Backwashing Operation

After the desired data has been collected the filter cake is flushed from the system. This is done by removing the connecting wires from the filter, closing all valves, and then opening valves A, E, C, and U. The flow of water will sweep the diatomite from the filter through the precoat pot to waste.

Determining the Polarity of the Filter Cake

The polarity of the filter cake is determined with a 1.5 volt dry cell battery. The recording potentiometer is turned on and the preliminary adjustments made. With the tracing pen recording a straight line in the center of the chart the wire which is connected to the downstream side of the filter is connected to the positive pole of the battery. Next the wire which is connected to the upstream side of the filter is briefly touched to the negative pole of the battery; the recording pen will move, for example, to the right.

When a run is being made, the recording pen will record a streaming potential for a given flow rate. If the flow rate is increased, the streaming potential is proportionally increased. If an increase in flow rate causes the recording pen to move to the right, the downstream electrode is positive. Therefore it is concluded that the filter cake is electronegative and the zeta potential is negative.

APPENDIX B: SAMPLE DATA AND CALCULATIONS

Data from a typical run, number 55, are presented below (also Fig. 15):

Table 4. Test Data

Polyelectrolyte	B_4	Run	55
$\frac{\text{lb Polyelectrolyte}}{\text{lb Celite 545}}$	0.00400	Part	b
Weight of Celite 545	5.0 gms	Date	July 22, 1963

Flow Rate cc/sec	Head Loss cm[a]	Resistance ohms	Temperature °C	Change in Streaming Potential mv
3.54	13.1	103,600	31.4	43.3
2.61	9.6		31.4	38.8
1.76	6.4		31.4	
3.54	12.9	103,600	32.2	

[a] Specific gravity of manometer fluid = 2.85.

In this run a slurry of diatomite, Celite 545, and polyelectrolyte B was mixed in the precoat pot for 15 minutes before precoating.

Impermeability Coefficient, K_3

From Eq. 5, K_3 may be calculated.

$$K_3 = \frac{H}{Q\,W_l}\,\frac{\eta_o}{\eta_t} \qquad (5)$$

Where: K_3 = impermeability coefficient at 20.3°C,

$$\frac{\text{ft}^5}{\text{gpm lb}}$$

H = head loss through the filter cake, feet of water

Q = flow rate, gpm/ft^2

W_1 = filter cake weight, lb/ft^2

η_t = absolute viscosity of the water at the test temperature centipoises

η_o = absolute viscosity of the water at 20.3°C, equal to 1.00 centipoises

Since K_3 is expressed in feet, pounds, and gpm, and the test data is recorded in centimeters, grams, and cubic centimeters per second, appropriate conversion factors are needed to convert to the desired units.

For the manometer fluid with a specific gravity of 2.85, the observed head loss, h, is related to H in the following manner:

$$H = h\,(2.85 - 1.00)\,\frac{0.0328 \text{ ft}}{1 \text{ cm}} = 0.0607\,h$$

For the 2 in. diameter septum the area is 0.0218 ft^2. Using this value the observed flow rate, q, is related to Q in the following manner:

$$Q = q\,\frac{0.0002642 \text{ gal}}{1 \text{ cc}}\;\frac{60 \text{ sec}}{1 \text{ min}}\;\frac{1}{0.0218 \text{ ft}^2} = 0.728\,q$$

The weight of diatomite, w, is related to W_1 in the following manner:

$$W_1 = w\,\frac{1 \text{ lb}}{453.6 \text{ gm}}\;\frac{1}{0.0218 \text{ ft}^2} = 0.101\,w$$

Substitution of these values of H, Q, and W_1 into Eq. 5 yields:

$$K_3 = \frac{0.825}{w}\;\frac{h}{q}\;\frac{\eta_o}{\eta_t}, \text{ in } \frac{\text{ft}^5}{\text{gpm lb}} \qquad (8)$$

Equation 8 is then used to compute K_3 from the test data. The value of $\frac{h}{q}$ is determined from a plot of h vs q (Fig. 16). The viscosity at 31.6°C is 0.775 centipoises, and at 20.3°C the viscosity is 1.00 centipoises (20.3°C is taken as standard temperature).

$$K_3 = \frac{0.825}{5.0}\;\frac{3.80}{1}\;\frac{1.00}{0.775} = 0.81\,\frac{\text{ft}^5}{\text{gpm lb}}, \text{ at } 20.3^\circ\text{C}$$

The impermeability coefficient, K_3, is corrected to a standard temperature to provide a value that can be compared for different filter aids tested at different temperatures.

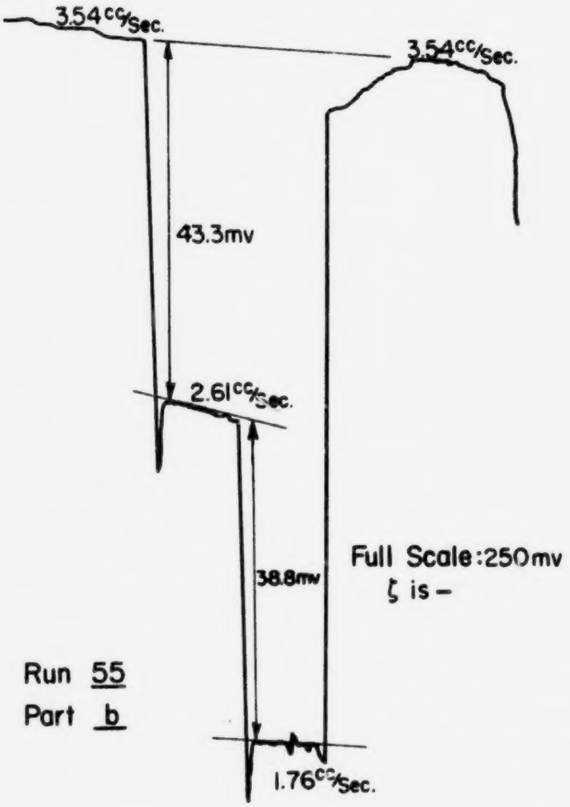


Fig. 15. Typical recording potentiometer chart

Zeta Potential

The apparent zeta potential is computed using Eq. 6.

$$\zeta_a = \frac{4\pi k E \eta}{DPR} \qquad (6)$$

Where:

ζ_a = zeta potential, mv
E = streaming potential, mv
D = dielectric constant of water
P = pressure difference across the filter cake, $\frac{kg}{meter\ sec^2}$
R = resistivity of the filtrate, ohm meters
4π = a constant
η = absolute viscosity of water, centipoises

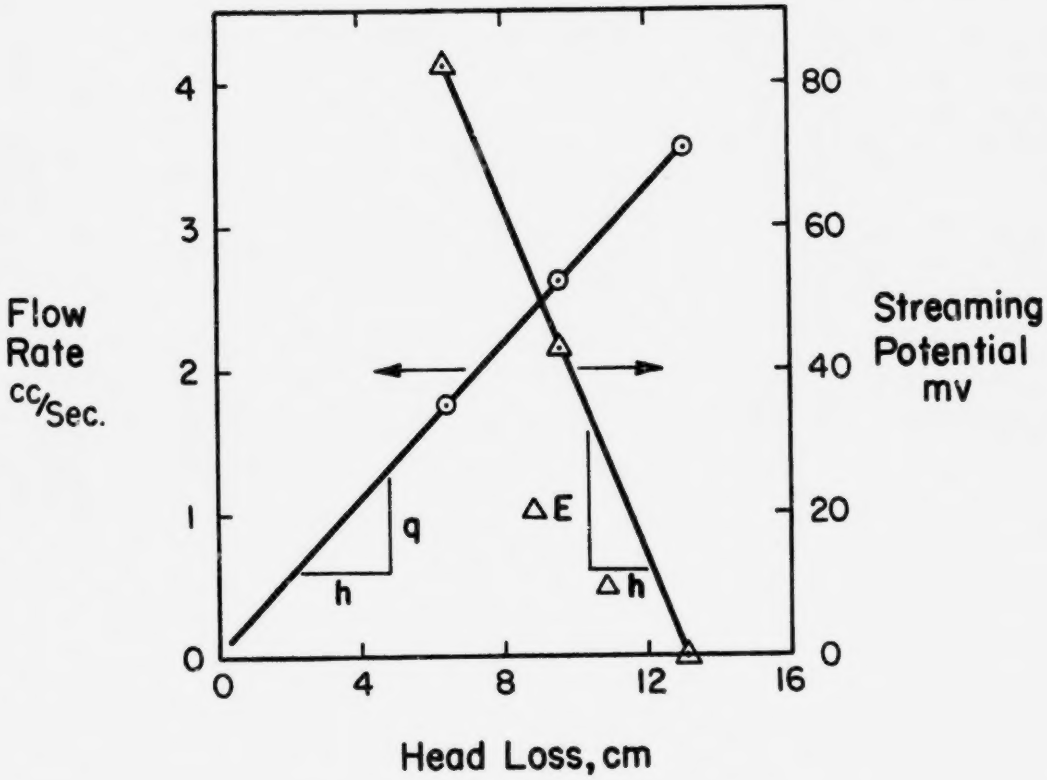


Fig. 16. Typical plots of flow rate, streaming potential, and head loss data (Run 55)

k = a proportionality constant ($8.99 \times 10^{9} \frac{\text{Newton meters}^2}{\text{Coulomb}^2}$) relating electrostatic units to practical electrical units.

For the test data the average temperature was 31.6°C and:

$$\eta = 0.775 \text{ centipoise} = 0.775 \times 10^{-3} \frac{\text{kg}}{\text{meters} \cdot \text{sec}^2}$$

$$D = 76.19$$

The specific resistivity of the filtrate is calculated by dividing the electrical resistance of the filtrate by the "cell constant", which was 37.5 meters^{-1}.

$$R = \frac{103,600}{37.5} = 2760 \text{ ohm meters}$$

A value of E/P is determined by plotting changes in E vs changes in P and finding the slope of the line. Figure 16 shows this plot.

$$\frac{E}{P} = -12.28 \frac{\text{mv}}{\text{cm (of manometer fluid)}}$$

To convert cm of manometer fluid into feet of water multiply by 6.07×10^{-2}, and to convert feet of water into the MKS system of units multiply by 3000.

$$\frac{E}{P} = \frac{-12.28}{(6.07 \times 10^{-2})\ (3000)} = -0.0674 \frac{\text{mv meters sec}^2}{\text{kg}}$$

The sign of the zeta potential is the same as that of the streaming potential. The value of the zeta potential is now computed as follows:

$$\zeta = \frac{(4\pi)\ (0.775 \times 10^{-3})\ (8.99 \times 10^{9})\ (-0.0674)}{(76.19)\qquad (2760)}$$

$$\zeta = -28.4 \text{ mv}$$

PART III

DIATOMITE FILTRATION EQUATIONS FOR FLAT AND CYLINDRICAL SEPTA

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Progress Report

DIATOMITE FILTRATION EQUATIONS FOR FLAT AND CYLINDRICAL SEPTA

by

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Division of Water Supply and Pollution Control
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DIATOMITE FILTRATION EQUATIONS FOR FLAT AND CYLINDRICAL SEPTA

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GENERAL

Solids removed during filtration ultimately form a cake on the surface of the original filter media as the solids clog the pores of the media. Filtration through the solids collected on the surface is commonly referred to as cake filtration. The larger the media relative to the suspended solids, the more time is needed to bridge the pores at the surface and form a filter cake because the solids penetrate further into the bed.

Suspended impurities in raw waters used for municipal water supplies almost invariably form compressible filter cakes that typically are resistant to flow. Rapid sand filter runs are, therefore, terminated at about the time a surface filter cake is beginning to form.

Cake filtration is a primary mode of removal in slow sand filtration, precoat carbon filtration, and diatomite filtration. However, in diatomite filtration, diatomite filter aid is added to the influent water as a body feed in order to form a porous incompressible cake. The action of the filter aid is to form a rigid mat with sufficient pore volume to accommodate the suspended impurities (4,5). The amount and type of body feed that should be added is an important consideration in the design of diatomite filtration plants.

In this paper, the filter aid placed on the filter aid support or septum before the start of a filter run is called the precoat. The term body feed will refer to the diatomite filter aid fed continuously to the influent during filtration. The term suspended solids or just solids will refer to the original solids in the water removed by filtration and will not include the body feed. The term filter cake will include only the filter cake composed of suspended solids and body feed and will not include the precoat.

PREVIOUS WORK ON DIATOMITE FILTRATION THEORY

In the following review of the theory of diatomite filtration, the nomenclature used by some of the investigators has been changed to conform to that of this paper for the sake of continuity. Each term used is defined where it first appears. Equations presented here will be in dimensionally homogeneous form using the basic dimensions of force, length, and time. A dimensionally homogeneous equation is one that can be used with any consistent set of basic units such as foot-pound-second, centimeter-gram-second, etc. Dimensions of terms will be indicated within brackets using the letters F (force), L (length), and T (time).

The filtration of water, especially diatomite filtration, is analogous to the flow of water through porous media. Thus, what is essentially D'Arcy's Law has been applied to filtration in the form of the generally accepted filtration rate equation. Although presented in many forms, probably the simplest is:

$$\frac{dV}{Adt} = \frac{dP}{\mu a dL} \tag{1}$$

where V = volume of filtrate $[L^3]$ filtered in time $t[T]$

A = gross cross-sectional area of porous media perpendicular to direction of flow $[L^2]$

dP/dL = pressure gradient $[FL^{-3}]$

μ = dynamic or absolute viscosity $[FTL^{-2}]$

a = specific resistance $[L^{-2}]$, and

L = thickness of porous media in direction of flow $[L]$.

This equation is probably the most useful tool available for dealing with cake-filtration problems. Its validity has been demonstrated by several workers including Carman (4, 5), Fair and Hatch (9), Ruth (15), Hoffing and Lockhart (11), Grace (10), and Kottwitch (12). Equation 1 can be changed to:

$$v = gi/\nu a \tag{2}$$

since $v = (1/A)dV/dt$ = approach velocity $[LT^{-1}]$

$i = dH/dL = dP/(dL\gamma_w)$ = hydraulic gradient [dimensionless]

$\nu = \mu g/\gamma_w$ = kinematic viscosity $[L^2T^{-1}]$

where γ_w = density of water $[FL^{-3}]$

H = head loss $[L]$

g = gravity constant $[LT^{-2}]$.

Comparison with D'Arcy's equation ($v = Ki$) illustrates that the specific resistance is inversely proportional to the coefficient of permeability ($a = g/K\nu$). The specific resistance a is typical of the filter medium.

Most research on filtration of water supplies has been done using sand as the filter media. Accordingly, most theories applicable to water filtration are based on use of sand (clean uniform sand at that) and have found little application in diatomite filtration.

There has been relatively little work done on the theory of diatomite filtration of water supplies. Fortunately, however, the theory of cake filtration is applicable; in fact, the theory is somewhat simplified by the action of filter aids. Carman demonstrated that a filter aid is efficient as a body feed in producing permeable filter cakes only if the proper proportion (with respect to the suspended solids) is used and that it is most efficient when mixed with suspended solids that would form compressible cakes without the filter aid (4,5). Small proportions of filter aid only add bulk to the cake with no increase in permeability. Large proportions add excessive thickness to the cake that overshadows the increase in permeability. Essentially the same thing was later demonstrated by Baumann and LaFrenz (1, 13, 14).

Equation 2 can be rewritten to express the head loss through the precoat and filter cake, respectively:

$$H_p = \frac{v\nu}{g} \left(\frac{a_p V_p}{A}\right) , \; H_c = \frac{v\nu}{g} \left(\frac{a_c V_c}{A}\right) \qquad (3)$$

since $i_p = H_p A/V_p$ and $i_c = H_c A/V_c$ where V_p and V_c are the volumes of precoat and filter cake $[L^3]$ and the subscripts p and c refer to the precoat and filter cake, respectively. The factors in parentheses represent what is usually called cake resistance. The specific resistance a represents the resistance of a unit volume of filter cake per unit area and is, therefore, referred to as the specific resistance based on the volume of filter cake.

Since the thickness of the filter cake is difficult to measure accurately, several workers have suggested that the specific resistance be referred to the weight of the filter cake by replacing the volume of the cake (V_c) in the above equation with the dry weight of the cake (W_c). Carman (4, 5) suggested that the specific resistance be referred to the weight of the solids (excluding body feed) in the filter cake (W_s) rather than the total weight of the filter cake (W_c).

In diatomite filtration of water supplies, sufficient body feed should be added to the influent to form an essentially incompressible filter cake. During a filter run the concentrations of suspended solids and body feed are generally constant. Therefore, the relative values of V_c, W_c, W_S, and even W_D (the weight of diatomite in the filter cake) remain the same, and the in-place bulk density of the filter cake (γ_c) is constant. Thus, the relative values of specific resistances based on volume of filter cake, weight of filter cake, weight of solids in the filter cake, or weight of diatomite in the filter cake would remain the same. If the specific resistance based on one of these four factors remains constant, then the specific resistances based on the other three factors also remain constant but differ in numerical value.

LaFrenz (13) developed a preliminary filtration head loss expression in 1961 which was found to be incorrect. The expression was corrected and, in 1962, Baumann, Cleasby, and LaFrenz expressed the head losses through the precoat and filter cake as follows (2):

$$H_p = K_3 vw \ , \ H_c = K_4 v W_D / A \qquad (4)$$

where $K_3 = 1/K_p \gamma_p$ $[F^{-1}L^2T]$

K_p = permeability of precoat $[LT^{-1}]$

γ_p = in place bulk density of the precoat $[FL^{-3}]$

w = precoat weight per unit area $[FL^{-2}]$

$K_4 = 1/K_c \gamma_p$ $[F^{-1}L^2T]$

K_c = permeability of filter cake $[LT^{-1}]$.

If Equation 3 is rewritten, referring the specific resistance to the weight of diatomite, then:

$$H_p = \frac{v\nu}{g} z_p w \ , \ H_c = \frac{v\nu}{g} \frac{z_c W_D}{A} \qquad (5)$$

where z = specific resistance based on weight of diatomite $[F^{-1}L]$.

Comparison of the filtration rate equations in Equations 4 and 5 illustrates that K_3 is proportional to the specific resistance of the precoat ($K_3 = Z_p\nu/g$) and K_4 is proportional to the specific resistance of the filter cake based on weight of diatomite in the filter cake ($K_4 = z_c\nu/g$).

The effect of viscosity is not included in Equation 4 and, therefore, both K_3 and K_4 are temperature dependent. For this reason, experimental K_3 and K_4 values were either referred to a standard temperature of 20°C by multiplying the value of K_3 or K_4 obtained at any temperature by the ratio of the viscosity at the test temperature to viscosity at 20°C (2, 6, 8), or experiments were conducted at the standard constant temperature.

In 1964, Baumann and Oulman published a modified form of the diatomite filtration equation (3) that accounted for viscosity. In dimensionally homogeneous form the expressions for H_p and H_c in the modified equation can be written:

$$H_p = v\nu\alpha_1 w/g^2 \ , \ H_c = v\nu\alpha_2 W_D/g^2 A \qquad (6)$$

where α_1 = factor of precoat resistance $[F^{-1}L^2T^{-2}]$

α_2 = factor of filter cake resistance $[F^{-1}L^2T^{-2}]$.

Comparison of Equation 6 with Equation 5 illustrates that the modified diatomite filtration equation is equivalent to the older filtration equation and that $\alpha_1 = z_p g$ and $\alpha_2 = z_c g$.

DIATOMITE FILTRATION EQUATIONS

At the beginning of a filter run, the filter housing is full of clean water from the precoating operation. The mixing of influent (unfiltered water) with the clean water in the housing results in a transition period that lasts until the quality of the water in the housing is the same as that of the influent. This transition period of initial dilution affects filtration results and should be accounted for in a diatomite filtration equation.

When filtering through cylindrical septa, the gross outer surface area of the filter cake perpendicular to the direction of flow (A) increases as the thickness of the cake increases. This increasing area has a significant effect on the head loss-time relationship for a filter run, especially when using small diameter septa. Therefore, a diatomite filtration equation is needed that accounts for increasing area effects.

No filtration equations that accounted for either the initial dilution effect or the effect of increasing area associated with cylindrical septa were found in the literature.

All previous diatomite filtration equations have been developed on the assumption that the surface area of the filter cake (A) remains constant. Throughout the remainder of this paper, septa that do not produce increasing area effects as filtration continues will be referred to as flat septa.

The effect of increasing area has negligible effect on the head loss through the precoat (H_p) because the precoat is so thin that its area is approximately equal to the area of the septum. Therefore, the expression for H_p in Equation 5 is valid for cylindrical septa and can be written in the following form:

$$H_p = q\nu\xi w/g \tag{7}$$

where $q = Q/A_s$ = flow rate per unit septum area or filtration rate $[LT^{-1}]$

Q = total plant flow rate $[L^3T^{-1}]$

A_s = total plant septum area $[L^2]$. The filter area may be provided in more than one filter and by use of multiple septums. Then, $A_s = 2\pi R_s L_s$ where R_s is the radius of the septum, and L_s is the combined length of all septa in the filters.

ξ = filter aid resistance index or ξ index = z_p by definition $[F^{-1}L]$.

Equation 7 is valid for any type of septum as long as the precoat is thin since A_s is approximately equal to the outer surface area of the precoat and the area of the precoated septum remains constant. The filter aid resistance index is equivalent to the specific resistance of the precoat based on the weight of diatomite and can be determined experimentally from Equation 7.

In Equation 2, v depends on the thickness of the cake for cylindrical filter cakes. Since v is directly proportional to i, the hydraulic gradient across a cylindrical filter cake is not constant throughout the cake and therefore is not equal to H_c/L_c. Thus, it must be expressed in differential form ($i_c = dH_c/dL_c$). Accordingly, Equation 2 expressing the head loss across the filter cake can be written:

$$dH_c = \frac{v\nu}{g} a_c dL_c \ . \tag{8}$$

Consider a cylindrical septum with radius R_s. Assuming that no solids pass through the cake, the small volume of filter cake formed during the interval of time dt is:

$$dV_c = Q\gamma_w S_f dt/\gamma_c \tag{9}$$

where dV_c = volume of filter cake formed in the time interval dt$[L^3]$

S_f = weight fraction of solids-body feed (both solids and body feed) in the water in the filter housing [dimensionless].

At the beginning of the run S_f is less than S_i (weight fraction of solids-body feed in the influent) because of initial dilution. S_f can be written in terms of S_i, however, if the filter is assumed to be a completely-mixed system. In a small increment of time Δt, the weight of solids-body feed that enters the filter and the weight of solids-body feed removed from the water in the filter are respectively $Q\gamma_w S_i \Delta t$ and $Q\gamma_w S_f \Delta t$. The change in weight of solids-body feed in suspension in the filter is therefore $\Delta W = Q\gamma_w(S_i - S_f)\ \Delta t$. Dividing through by the weight of water in the filter yields:

$$\frac{\Delta W}{V_f \gamma_w} = \frac{Q\gamma_w(S_i - S_f)\Delta t}{V_f \gamma_w} \Longrightarrow \Delta S_f = \delta(S_i - S_f)\ \Delta t$$

where $\Delta S_f = \Delta W/V_f \gamma_w$

δ = Q/V_f = theoretical dilution rate $[T^{-1}]$

V_f = volume of the filter housing on the new water side of the filter media $[L^3]$.

Passing to the limit leads to the differential equation that can be integrated:

$$\int \frac{dS_f}{S_i - S_f} = \int \delta dt \Longrightarrow \ln(S_i - S_f) = -\delta t + c \Longrightarrow S_i - S_f = e^{-\delta t} e^{c}$$

where c = an integration constant. For the initial condition $S_f = 0$ at $t = 0$, $e^c = S_i$, and:

$$S_f = S_i(1 - e^{-\delta t}) = (C_S + C_D)\ (10)^{-6}(1 - e^{-\delta t}) \qquad (10)$$

since $S_i = (C_S + C_D)\ (10)^{-6}$

where C_S = concentration of solids in ppm and

C_D = concentration of body feed in ppm.

Substitution for S_f in Equation 9 yields:

$$dV_c = \frac{Q\gamma_w}{\gamma_c}(C_S + C_D)\ (10)^{-6}(1 - e^{-\delta t})dt. \qquad (11)$$

Now, let us assume that the solids removed in the filter cake do not increase the cake thickness appreciably over the thickness that would result if the cake contained only body feed. This is equivalent to saying that:

$$\frac{C_D}{\gamma_p} \text{ is approximately equal to } \frac{(C_S + C_D)}{\gamma_c} \qquad (12)$$

Substitution of C_D/γ_p for $(C_S + C_D)/\gamma_c$ in Equation 11 leads to:

$$dV_c = \frac{Q\gamma_w}{\gamma_p} C_D\ (10)^{-6}\ (1 - e^{-\delta t})dt \qquad (13)$$

Since $dL_c = dV_c/A$, substitution for dL_c in Equation 8 yields the differential equation for diatomite filtration:

$$dH_c = \frac{v\nu}{g} a_c \left[\frac{Q\gamma_w}{A\gamma_p} C_D (10)^{-6}(1 - e^{-\delta t})dt\right] \Longrightarrow$$

$$dH_c = \frac{v^2\nu}{g}\left[\frac{a_c\gamma_w}{\gamma_p}(10)^{-6}\right] C_D (1 - e^{-\delta t})dt \Longrightarrow$$

$$dH_c = \frac{v^2\nu}{g}\beta C_D (1 - e^{-\delta t})dt \tag{14}$$

where, for convenience, $\beta = a_c\gamma_w(10)^{-6}/\gamma_p$, and will be denoted as the cake resistance or β index $[L^{-2}]$. The cake resistance index remains constant during a filter run and can be determined experimentally. β is essentially equal to a constant $(\gamma_w(10)^{-6})$ times the specific resistance of the filter cake based on weight of diatomite (z_c) since $z_c = a_c/\gamma_p$ if Equation 12 is valid.

The surface area of the cylindrical septa is $A_s = 2\pi R_s L_s$, and the gross outer filter area of a cylindrical filter cake of radius R is $A = 2\pi RL_s$. Thus, $A = A_s(R/R_s)$ and $v = Q/A = Q/A_s(R/R_s) = qR_s/R$. Substitution for v in Equation 14 gives:

$$dH_c = \left[\frac{q^2R_s^2}{R^2}\right]\frac{\nu}{g}\beta C_D(1 - e^{-\delta t})dt \Longrightarrow$$

$$dH_c = \frac{R_s^2\sigma(1 - e^{-\delta})dt}{R^2} \tag{15}$$

where, for convenience, $\sigma = q^2\nu\beta C_D/g\ [LT^{-1}]$. The parameter σ remains constant during a filter run.

The total volume (V_T) enclosed within the outer surface area of a filter cake of radius R is:

$$V_T = V_s + V_p + V_c = \pi R^2 L_s$$

where V_s = volume of septum $[L^3]$, and

L_s = total length of all septa in the filters [L].

Differentiating:

$$dV_T = dV_c = 2\pi L_s R dR \tag{16}$$

since $dV_s = dV_p = 0$. Equating the right hand sides of Equation 13 and 16 leads to:

$$2\pi L_s R dR = \frac{Q\gamma_w C_D (10)^{-6}}{\gamma_p} (1 - e^{-\delta t}) dt \Longrightarrow$$

$$2RdR = \left[\frac{2R_s}{2R_s}\right] \frac{Q\gamma_w C_D (10)^{-6}}{\pi L_s \gamma_p} (1 - e^{-\delta t}) dt$$

Since $q = Q/A_s = Q/2\pi R_s L_s$, therefore:

$$2RdR = R_s \left[\frac{2q\gamma_w C_D (10)^{-6}}{\gamma_p}\right] (1 - e^{-\delta t}) dt$$

$$= R_s \varphi \, (1 - e^{-\delta t}) dt \tag{17}$$

where, for convenience, φ is defined as $2q\gamma_w C_D (10)^{-6}/\gamma_p$. ϕ remains constant during a filter run and has the dimensions $[LT^{-1}]$. This differential equation can be integrated as follows:

$$\int_{R_o}^{R} 2RdR = R_s \varphi \int_{o}^{t} (1 - e^{-\delta t}) dt \Longrightarrow$$

$$R^2 \Big]_{R_o}^{R} = R_s \varphi \left[t + \frac{e^{-\delta t}}{\delta}\right]_o^t = R_s \varphi \left[t + \frac{e^{-\delta t}}{\delta} - \frac{1}{\delta}\right] \Longrightarrow$$

$$R^2 = R_o^2 + R_s\phi\left[t - \frac{1 - e^{-\delta t}}{\delta}\right] = R_o^2 + R_s\phi x \qquad (18)$$

where $x = t - (1 - e^{-\delta t})/\delta$ [T] and

$R_o = R_s + L_p = R_s + w/\gamma_p = R$ at $t = 0$.

Notice that x is equal to t decreased by the factor $(1 - e^{-\delta t})/\delta$. Thus, the action of initial dilution is, in effect, a time delay equal to $(1 - e^{-\delta t})/\delta$. This time delay factor decreases with increasing δ, and for very large δ, x is approximately equal to t. Also, dx is approximately equal to dt for large values of t since:

$$dx = dt - \frac{\delta e^{-\delta t} dt}{\delta} = (1 - e^{-\delta t})dt.$$

Substitution of the expression for R^2 (Equation 18) in Equation 15 and integration leads to an expression for H_c, as follows:

$$dH_c = \frac{R_s^2\sigma\,(1 - e^{-\delta t})dt}{R_o^2 + R_s\phi x} = \frac{R_s^2\sigma dx}{R_o^2 + R_s\phi x} \implies$$

$$\int_o^{H_c} dH_c = \frac{R_s^2\sigma}{R_s\phi}\int_o^{x}\frac{R_s\phi dx}{R_o^2 + R_s\phi x} = \frac{R_s\sigma}{\phi}\left[\ln(R_o^2 + R_s\phi x)\right]_o^x \implies$$

$$H_c = \frac{R_s\sigma}{\phi}\left[\ln(R_o^2 + R_s\phi x) - \ln R_o^2\right] = \frac{R_s\sigma}{\phi}\ln\left(1 + \frac{R_s\phi x}{R_o^2}\right) \qquad (19)$$

In deriving Equation 19, the following hypotheses were assumed to be true during a filter run:

1. Q remains constant (constant rate filtration).
2. The body feed rate is sufficient to form an incompressible filter cake.

3. The filtration rate equation in differential form (Equation 8) is valid for cylindrical filter cakes.
4. γ_p and γ_c remain constant.
5. C_S and C_D remain constant.
6. No solids pass through the cake.
7. There are no concentration gradients in the filter housing (completely-mixed system).
8. Equation 12 is valid -- i.e., the solids retained in the filter cake do not increase the cake thickness appreciably.

If these hypotheses are true, then the flow resistive indexes (ξ and β) remain constant for a particular run and can be determined experimentally.

Equation 19 is a significant improvement over previously published equations for finding the head loss across the filter cake:

1. It includes the effect of initial dilution at the beginning of a filter run.
2. It includes the effect of increasing area for cylindrical septa.
3. It is derived from an equation that includes the effect of viscosity.
4. It is dimensionally homogeneous and therefore can be used with any consistent set of units without modification (ft-lb-hr are convenient English units).

For very large diameter septa (a flat septum would have an infinite diameter) Equation 19 can be simplified since ln(1 + x) is approximately equal to x for small values of x, and R_s is approximately equal to R_o for large values of R_s:

$$H_c = \frac{R_s\sigma}{\phi}\left[\frac{\frac{R_s\varphi x}{2}}{R_o}\right] \Longrightarrow$$

$$H_c = \sigma x \tag{20}$$

The use of t in place of x in Equation 20 conforms to previous equations that do not include dilution effects or the increasing area effects resulting from use of cylindrical septa (Equations 4 and 6).

The total thickness of precoat and filter cake ($L = L_p + L_c$) at time t for cylindrical septa can be determined from Equation 18, and is equal to:

$$L = R - R_s = \sqrt{R_o^2 + R_s\varphi x} - R_s \tag{21}$$

For flat septa, $dV_c = A_s dL_c$. Equating this expression for dV_c to the right hand side of Equation 13 leads to:

$$A_s dL_c = \frac{QY_w}{Y_p} C_D(10)^{-6}(1 - e^{-\delta t})dt = A_s \frac{\phi}{2} dx$$

since $A_s\varphi = 2QY_wC_D(10)^{-6}/Y_p$. Integration leads to:

$$\int_o^{L_c} dL_c = \frac{\varphi}{2}\int_o^x dx \Longrightarrow L_c = \frac{\varphi x}{2}$$

$$L = L_p + \frac{\varphi x}{2} \tag{22}$$

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The basic equation for the total filtration head loss is:

$$H = (H_e + H_p) + H_c = H_o + H_c \tag{23}$$

which states that the total head loss is equal to the sum of the head losses through the equipment, H_e, (piping, septum, etc.), the precoat, and the filter cake. H_o is the initial head loss at $t = 0$. Since $H_c = 0$ at $t = 0$, $H_o = H_e + H_p$.

The Equations for head loss through the precoat (H_p), head loss through the filter cake (H_c), and the combined thickness of the precoat and filter cake (L) for both flat and cylindrical septa are summarized in Table 1. The expressions for the combined thickness of the precoat and filter cake are included because, in some cases, this thickness limits the length of filter run before the terminal head loss is reached. This possibility was not considered in LaFrenz' procedure for determining the optimum combination of flow rate, body feed concentration, and terminal head loss (13).

The diatomite filtration equations for flat and cylindrical septa presented have been verified for filter cakes containing iron, clay, and carry-over from the lime-soda ash softening process (7). The equations should be valid for water containing any type of solid as long as the hypotheses assumed in their derivations are satisfied.

TABLE 1. SUMMARY OF DIATOMITE FILTRATION EQUATIONS

(Any septum)	$H_p = q\nu\xi w/g$	(7)
(Cylindrical septum)	$H_c = \frac{R_s \sigma}{\varphi} \ln(1 + \frac{R_s \varphi x}{R_o^2})$	(19)
	$L = \sqrt{R_o^2 + R_s \varphi x} - R_s$	(21)
(Flat septum)	$H_c = \sigma x$	(20)
	$L = L_p + \frac{\varphi x}{2}$	(22)

$\sigma = q^2 \nu \beta C_D/g\ [LT^{-1}]$

$\varphi = 2q\gamma_w C_D (10)^{-6}/\gamma_p\ [LT^{-1}]$

$x = t - (1 - e^{-\delta t})/\delta\ [T]$

$\delta = Q/V_f\ [T^{-1}]$

$R_o = R_s + L_p [L]$

$L_p = w/\gamma_p\ [L].$

DETERMINATION OF β INDEX

Figure 1 illustrates the theoretical head loss-time relationships for the hypothetical conditions indicated in the figure using a flat septum and two cylindrical septa, one of 3.50 inch and one of 1.00 inch diameter. The curves in Fig. 1 were determined by computing the head loss ($H_o + H_c$) at one hour increments. H_c was computed from Equation 20 for curve A and from Equation 19 for curves B and C. The resulting theoretical head loss-time relationships during the first 25 hours of a filter run are shown in Fig. 1.

Previous diatomite filtration equations (2, 3) that account for neither initial dilution nor increasing area describe a linear head loss-time curve for all values of time (equivalent to substituting t for x in Equation 20). Figure 1 illustrates that the linear equations can be used to determine cake resistance only when flat septa are used since only curve A becomes linear with increasing time. Linear equations were used previously to determine K_4 (Equation 4) and α_2 (Equation 6) by plotting head loss versus time and measuring the slope of the straight line of best fit, neglecting points in the transition zone affected by initial dilution. Using linear equations to determine cake resistance when using cylindrical septa is essentially the same as saying that curves A, B, and C in Fig. 1 are all the same curve. This is obviously not the case. It should be recognized, therefore, that there would be poor correlation of results of runs under similar conditions using flat and cylindrical septa when using the old equations. LaFrenz found this to be true (13).

Thus, the effect of the increasing area using cylindrical septa cannot be ignored. Further, cylindrical septa (especially those of small diameter) offer definite advantages over flat septa with respect to head loss increase with time.

When using the flat septa the β index can be determined from a plot of head loss versus time. The resulting curve should become linear with slope σ as illustrated by curve A of Fig. 1. β can then be computed from the definition of σ. The value of δ is not needed to determine β when using flat septa. The β index can also be determined from a plot of H versus x. The resulting curve should be linear with slope σ for all values of x in accordance with Equation 20. Even if the wrong value of δ is used, the plot of H versus x should become linear with slope σ.

When using cylindrical septa, the determination of the β index is more difficult. Its value cannot be determined from a plot of H versus t because the curve will not become linear. However, a plot of H versus the ln term of Equation 19 should be linear with slope $R_s\sigma/\phi$ as illustrated by the dashed curves in Fig. 2. β can then be computed using the definitions of σ and ϕ.

An approximate value of β can be determined by using t in place of x in the above plots as illustrated by the solid curves in Fig. 2; i.e., plot of H versus $\ln(1 + R_s\phi t/R_o^2)$. This approximation is more accurate for large values of t. The resulting curve should become linear with slope of approximately $R_s\sigma/\psi$.

When using cylindrical septa, the value of ψ and therefore the value of γ_p must be known to determine β accurately. This value was not needed for the previous linear equations, and consequently, few efforts were made in the past to measure it. However, when γ_p is not known, an approximate value of β can still be determined by trying different values of γ_p and choosing the γ_p (and its corresponding β index) that best fits the data. This procedure is somewhat indirect and involves more work than would be necessary if γ_p were known; but is a procedure that can be used when such a value is not available.

Further difficulty is encountered in determining the β index for cylindrical filter cakes because of initial dilution. The theoretical dilution rate (Q/V_f) is the dilution rate for a filter having no concentration gradients within its housing -- a condition seldom realized. The actual dilution rate often varies because of unsteady conditions during the first few minutes of a filter run such as occur due to changes in flow rate, body feed concentration, etc. When the dilution rate is large, as is the case in most commercial filters, good results can be obtained by approximating x with t and measuring the slope of the H versus $\ln(1 + R_s\phi x/R_o^2)$ curve (solid curves in Fig. 2). But when the dilution rate is small, this approximation may be inadequate. In these cases, a value of δ should be estimated from the data. This can be done by a trial and error procedure (7).

The difficulties in determining the β index for cylindrical filter cakes are caused by the fact that the rate of head loss increase (dH/dt) is dependent on the thickness of the cake (Equation 15). Using flat septa, dH/dt is independent of cake thickness.

For accurate evaluation of the β index the filter runs should extend well past the transition period caused by the initial dilution.

Also, when using cylindrical septa, special effort should be made to keep C_S, C_D, and Q constant during the run, including the transition period.

Even though γ_p must be known to determine β accurately for cylindrical cakes, a good approximation of the head loss-time curve can be obtained when using an estimated value of γ_p. An error in γ_p results in a corresponding error in β. However, the use of an erroneous β index in the prediction of head loss-time relationships for cakes formed on cylindrical septa of the same diameter used for determining β, is relatively insensitive to errors in γ_p (7).

The accuracy of prediction for cakes formed on septa of different size or shape, however, is much more sensitive. Therefore, the diameter of the septum used and the value of γ_p used to determine the β indexes for cylindrical cakes should be stated.

SUMMARY AND CONCLUSIONS

Previously developed diatomite filtration equations have been found to be invalid for use with cylindrical septa (7). They are inadequate because they fail to describe the significant effect of the increasing filtering area associated with cylindrical filter cakes. Also, they do not describe the initial transitional period resulting from initial mixing of the influent with the clean water in the filter left over from the precoating operation (dilution effect).

The initial dilution effect is less important and can probably be ignored for most practical applications. The increasing area effect, however, should not be ignored.

Diatomite filtration equations were developed theoretically herein from the generally accepted filtration rate equation. The hypotheses assumed in the derivation of these equations are explicitly stated. These equations account for the effects of both initial dilution and increasing area.

The following conclusions are offered:

1. The diatomite filtration head loss equations for flat septa (Equation 20) and cylindrical septa (Equation 19) can be used to describe the head loss-time relationships, including the brief transitional period at the beginning of a filter run, for filter cakes containing several different types of filtered solids. These equations have been verified for filter cakes containing iron, clay, and carry-over from the lime-soda ash softening process (7).

2. Head loss through the filter cake is a linear function of time for flat septa and a logarithmic function of time for cylindrical septa, except for a brief initial transitional period.
3. The rate of head loss increase is less with cylindrical septa than with flat septa, other things being equal. The smaller the septum diameter, within practical limits, the lower the resulting rate of head loss increase.
4. A relatively accurate description of the head loss-time curves for filter cakes can be obtained even when approximate values of precoat bulk density (γ_p) are used in the determination of the filter cake resistance index (β index). However, the use of approximate values of γ_p result in approximate values of the β index. Thus, the value of γ_p and the type of septum used in the determination of the β index should be additionally stated with the value of the β index.
5. The diatomite filtration equations presented herein can be used to determine filter cake resistance, and to predict filter performance under different operating conditions.

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PART IV

PREDICTION OF DIATOMITE FILTER CAKE RESISTANCE

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Progress Report

PREDICTION OF DIATOMITE FILTER CAKE RESISTANCE

by

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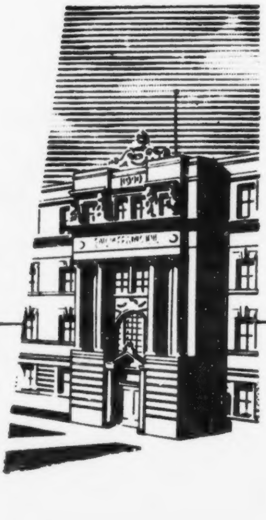
United States Public Health Service
Division of Water Supply and Pollution Control
Research Grant WP-00196

Project 549-S

Municipal Diatomite Filters

January 3, 1966



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PREDICTION OF DIATOMITE FILTER CAKE RESISTANCE

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January 3, 1966

BACKGROUND

Recently, diatomite filtration equations for flat and cylindrical septa were developed theoretically from the filtration rate equation (7, 9). These equations are summarized in Table 1.

The head loss through a diatomite filter cake can be determined by adding the head loss through the body feed plus suspended solids filter cake to the head loss through the precoat and its supporting septum. The head loss through the precoat can be determined using Equation 1. The head loss through the filter cake which forms as the filter run progresses can be determined from either Equation 2 or 4 depending, respectively, on whether cylindrical or flat septa are used. Equation 4 represents a special case of Equation 2 and is applicable when R_s, the radius of a cylindrical septum, approaches infinity. Equations 3 and 5 can be used to determine the thickness of the filter cakes which will result on cylindrical and flat septa, respectively. The thickness of the filter cakes will determine the spacing which must be used between septa in the filter design.

Figure 1 shows the theoretical head loss versus time of filtration curves that would result from filtration of the same water through the same total area of filter using flat and cylindrical septa. The curves represent plots obtained using Equation 1 to determine the initial head loss at time zero and using Equation 2 and 4, respectively, to determine the increase in head loss with time using cylindrical and flat septa.

Figure 1 indicates quite clearly the very significant effect of diameter of cylindrical septa on head loss progression.

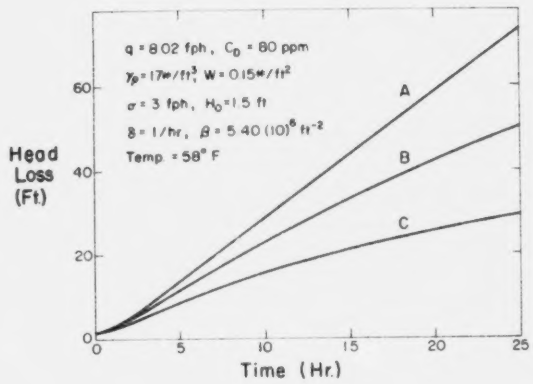

Fig. 1. Theoretical head loss versus time curves for conditions indicated

Curve A - flat septum
Curve B - 3.50 inch diameter
Curve C - 1.00 inch diameter

Table 1. Summary of Diatomite Filtration Equations

(Any septum)

$$H_p = q\nu\xi w/g \tag{1}$$

(Cylindrical septum)

$$H_c = \frac{R_s\sigma}{\phi}\ \ln(1 + \frac{R_s\phi x}{R_o^2} \tag{2}$$

$$L = \sqrt{R_o^2 + R_s\phi x} - R_s \tag{3}$$

(Flat septum)

$$H_c = \sigma x \tag{4}$$

$$L = L_p + \frac{\phi x}{2} \tag{5}$$

$\sigma = q^2\nu\beta C_D/g\ [LT^{-1}]$

$\phi = 2q\gamma_w C_D(10)^{-6}/\gamma_p\ [LT^{-1}]$

$x = t - (1 - e^{-\delta t})/\delta\ [T]$

$\delta = Q/V_f\ [T^{-1}]$

$R_o = R_s + L_p\ [L]$

$L_p = w/\gamma_p\ [L]$

(Definition of terms on next page)

Symbol	Meaning
A_s	Septum area $[L^2]$
β	Filter cake resistance index or β index $[L^{-2}]$
C_D	Body feed concentration, ppm by weight
C_S	Suspended solids concentration, ppm by weight
δ	Dilution rate, theoretically Q/V_f $[T^{-1}]$
g	Gravity constant $[LT^{-2}]$
γ_p (γ_c)	Bulk density of precoat (filter cake) $[FL^{-3}]$
γ_w	Density of water
H_p (H_c)	Head loss through precoat (filter cake) $[L]$

Symbol	Meaning
L_p (L_c)	Thickness of precoat (filter cake) $[L]$
L	$L_p + L_c$ $[L]$
ν	Kinematic viscosity $[L^2T^{-1}]$
Q	Flow rate $[L^3T^{-1}]$
q	Flow rate per unit septum area (filtration rate, Q/A_s) $[LT^{-1}]$
R_s	Radius (outer) of septum $[L]$
t	Time $[T]$
w	Precoat weight per unit area $[FL^{-2}]$
x	$t - (1 - e^{-\delta t})/\delta$ $[T]$
ξ	Filter aid resistance index or ξ index $[F^{-1}L]$
z_c	Specific cake resistance based on weight of diatomite in filter cake $[F^{-1}L]$
V_f	Volume of filter housing $[L^3]$

The head loss during filtration is a logarithmic function of time for cylindrical septa and a linear function of time for flat septa. The function is non-linear for cylindrical septa because the filtering surface area of a cylindrical filter cake grows larger as the filter cake grows thicker and is thus time dependent. This produces a decrease as compared with flat septa, in the rate of head loss accretion; this is referred to as the "increasing area effect" (7,9).

In previous papers, filter cake resistance parameters, K_4 (1) and α_2 (4), were determined on the basis of linear head loss equations similar to Equation 4 from data collected using both flat and cylindrical filter cakes. In all cases, the cylindrical septa used had a diameter of 3.5 inches. With the short filter runs used, the error made by assuming a constant filter area throughout the run was not considered significant.

In this study, the resistances of all filter cakes, represented by their β-indices, were determined by using the appropriate filtration head loss equation in Table 1. Previously published (1,5,10,11,15,16) filter cake resistance data were reanalyzed on the basis of the newly-developed equations to provide cake resistances in terms of their β-indices. Most of the previously published filter cake resistance data was for runs made using iron-bearing waters. Additional studies were made, therefore, to provide cake resistance data on the removal of various clays and softening sludges from suspension by diatomite filtration. The results, as will be made evident in this paper, verify the applicability of the equations in Table 1.

The equations in Table 1 were derived on the basis of the following hypotheses (7,9):

1. Constant rate filtration (Q-constant).
2. Use of sufficient body feed to form an incompressible filter cake.
3. The in-place bulk densities of the precoat (γ_p) and filter cake (γ_c) remain constant.
4. The concentration of solids being filtered (C_S) and the body feed concentration (C_D) remain constant.
5. No solids pass through the cake.
6. No concentration gradients exist in the filter housing (completely-mixed system).
7. The solids retained in the filter cake do not increase the cake thickness appreciably.

If these hypotheses are "reasonably" valid for a particular filter run, the β index will remain constant during the run. However, this index will vary from one run to the next as the water quality changes or as changes are made in C_D. From a practical viewpoint, the engineer is interested in estimating or predicting filter cake resistance under such varying conditions - i.e., for different values of C_S and C_D when filtering a particular water using a particular filter aid grade. A method of predicting the β index is presented herein that involves the use of empirical prediction equations.

FILTRATION DATA

The data from filter runs made by different investigators were analyzed in this study. The data include results from filter runs made using flat septa and 3.5 inch diameter cylindrical septa. All runs were made for the purpose of determining filter cake resistance. Each run was assigned a symbolic code number (ID) for identification and reference and a suspended solids (SS) code number to indicate the type of solid removed by filtration. The ID code numbers are all four or six digit numbers used to indicate the investigator, the run series number, the filter number, the investigator's run number, or the body feed concentration. Each run was made using one of six different types of suspended solids assigned code numbers from 1 to 6. A detailed explanation of the ID and SS code numbers and a summary of all the runs analyzed in this study are included in Table 2.

FILTERS

The different types of filters used to collect the data have been described by the various investigators, and only brief descriptions will be presented here.

The first digit of the filter run ID number identifies the particular group of filter runs. Filter runs beginning with the digit 1 were made by Regunathan (15,16) using Iowa State University tap water containing either Kentucky ball clay consisting mostly of kaolinite, or Wyoming bentonite consisting mostly of montmorillonite. These waters will be referred to in subsequent discussion by the type of clay they contain. These filter runs were made using a pressure filter containing 3.5 inch diameter septa. This pressure filter has been referred to as the pilot plant and has been used in several investigations at Iowa State University (1,10,11,12,15,16). In all of the Regunathan runs listed in Table 2, turbidity units were used as a relative measure of C_S.

Table 2.

SUMMARY OF FILTER RUNS

ID = FILTER RUN IDENTIFICATION CODE NUMBERS:

REGUNATHAN RUNS. FIRST DIGIT = 1
SECOND DIGIT = 2 FOR SERIES B
= 3 FOR SERIES C
= 4 FOR SERIES D
LAST TWO DIGITS = RUN NUMBER
FOYSTER RUNS. FIRST DIGIT = 2
LAST THREE DIGITS = RUN NUMBER
LAFRENZ RUNS. FIRST DIGIT = 3
NEXT TWO DIGITS = VHP SERIES NUMBER
LAST THREE DIGITS = BODY FEED CONCENTRATION (CD)
(LAFRENZ CODE NUMBER SIX DIGITS LONG, ALL OTHERS FOUR)
EXTRA RUNS. FIRST DIGIT = 4
LAST THREE DIGITS = RUN NUMBER
HALL AND HAWLEY RUNS. FIRST DIGIT = 5
LAST THREE DIGITS = RUN NUMBER
LOMPOC, CALIFORNIA PLANT-SCALE RUNS. (DILLINGHAM). FIRST DIGIT = 6
SECOND DIGIT = FILTER NUMBER
LAST TWO DIGITS = RUN NUMBER
AMES, IOWA PLANT RUNS (MOBILE UNIT). FIRST DIGIT = 7
LAST THREE DIGITS = RUN NUMBER

EXAMPLES

1206	REGUNATHAN, SERIES B, RUN 6
2009	FOYSTER, RUN 9
312100	LAFRENZ, SERIES VHP-12, 100 PPM BODY FEED
4024	EXTRA RUN NUMBER 24
5155	HALL AND HAWLEY, RUN 155
6320	LOMPOC, FILTER 3, RUN 20
7015	AMES, MOBILE UNIT, RUN 15

R = CORRELATION COEFFICIENT IN PERCENT

SS = SUSPENDED SOLIDS CODE NUMBER

1 = FERROUS SULFATE ADDED TO UNIVERSITY TAP WATER
2 = FERRIC CHLORIDE ADDED TO UNIVERSITY TAP WATER
3 = FERROUS CHLORIDE ADDED TO UNIVERSITY TAP WATER
4 = KENTUCKY BALL CLAY ADDED TO UNIVERSITY TAP WATER
5 = WYOMING BENTONITE ADDED TO UNIVERSITY TAP WATER
6 = EFFLUENT FROM LIME SODA ASH PROCESS
(FOR FILTER RUNS FILTERING SS 4, 5, OR 6, CS = TURBIDITY)

ID	q GSFM	C_S PPM	C_D PPM	ξ 10^9 FT/LB	β 10^4 FT^{-2}	R %	SS
1203	1	37	110	0.822	193	99.975	4
1204	1	37	211	0.822	63	99.975	4
1208	1	108	133	0.822	1230	99.992	4
1209	1	115	126	0.822	1850	99.976	4
1215	1	119	213	0.822	444	99.963	4
1304	1	68	74	5.50	4740	99.993	4
1305	1	90	90	5.50	4720	99.965	4
1311	1	92	94	5.50	5692	99.977	4
1314	1	88	105	5.50	3244	99.979	4
1315	1	92	149	5.50	1714	99.981	4
1404	1	78	599	5.50	3446	99.972	5
1406	1	91	495	5.50	4800	99.969	5
1407	1	93	410	5.50	11250	99.983	5
1409	1	85	1033	5.50	740	99.990	5
1410	1	45	336	5.50	5150	99.986	5
1412	1	46	347	5.50	5420	99.996	5
1414	1	46	365	5.50	4140	99.988	5
1415	1	85	670	5.50	2400	99.996	5
1416	1	32	254	5.50	7070	99.948	5
2009	1	7.4	120	0.78	256		1
2010	1	7.4	40	2.76	2931		1
2011	1	7.3	40	2.76	2974		1
2012	1	7.6	80	2.76	1063		1
2013	1	7.4	120	2.76	334		1
2014	1	7.3	40	0.73	2069		1
2016	1	7.4	80	0.73	586		1
2018	1	7.4	120	0.73	283		1
2019	1	7.2	40	0.78	2478		1
2020	1	7.3	40	0.78	1939		1
2021	2	7.7	80	0.78	340		1
2022	2	7.3	120	0.78	150		1
2024	2	7.6	80	0.78	424		1
2025	2	7.5	80	0.78	318		1
2026	2	7.2	80	0.78	366		1
302020	1	7.0	20	0.75	4686		1
302040	1	7.5	40	0.75	1544		1
302060	1	7.4	60	0.75	615		1
302080	1	7.3	80	0.75	319		1
302100	1	7.5	100	0.75	169		1
302160	1	7.1	160	0.75	73		1

ID	q GSFM	C_S PPM	C_D PPM	ξ 10^9 FT/LB	β 10^4 FT^{-2}	R %	SS
302400	1	6.7	400	0.75	22.0		1
302800	1	6.9	800	0.75	0.90		1
303020	2	7.4	20	0.75	1867		1
303040	2	7.4	40	0.75	1237		1
303060	2	7.4	60	0.75	727		1
303080	2	7.4	80	0.75	450		1
303100	2	7.4	100	0.75	288		1
303120	2	7.4	120	0.75	187		1
303140	2	7.4	140	0.75	107		1
303160	2	7.4	160	0.75	75		1
303200	2	7.4	200	0.75	51.2		1
303300	2	7.4	300	0.75	30.0		1
304020	3	7.4	20	0.75	1717		1
304040	3	7.4	40	0.75	1248		1
304060	3	7.4	60	0.75	520		1
304100	3	7.4	100	0.75	197		1
304130	3	7.4	130	0.75	142		1
304140	3	7.4	140	0.75	42.7		1
304160	3	7.4	160	0.75	24.7		1
305020	2	4.0	20	0.75	1440		1
305040	2	4.0	40	0.75	514		1
305060	2	4.0	60	0.75	193		1
305080	2	4.0	80	0.75	128		1
305100	2	4.0	100	0.75	78		1
305160	2	4.0	160	0.75	39		1
309020	1	2.0	20	0.75	750		1
309060	1	2.0	60	0.75	124		1
309100	1	2.0	100	0.75	48		1
309160	1	2.0	160	0.75	18.7		1
310030	3	4.0	30	0.75	937		1
310060	3	4.0	60	0.75	258		1
310100	3	4.0	100	0.75	85.5		1
310120	3	4.0	120	0.75	57.0		1
310160	3	4.0	160	0.75	33.4		1
312020	3	7.4	20	0.75	2504		1
312040	3	7.4	40	0.75	1035		1
312080	3	7.4	80	0.75	371		1
312100	3	7.4	100	0.75	226		1

ID	q GSFM	C_S PPM	C_D PPM	ξ 10^9 FT/LB	β 10^4 FT^{-2}	R %	SS
4006	0.94	7.6	39.9	0.78	4252	99.971	1
4007	0.94	7.5	160	0.78	342	99.917	1
4012	0.94	3.8	82	0.78	294	99.969	1
4013	0.94	1.9	19.6	0.78	2238	99.992	1
4015	2.18	7.6	60	0.78	1994	99.896	1
4017	2.18	7.6	160	0.78	247	99.925	1
4018	2.18	8.1	172	0.78	210	99.985	1
4019	2.18	7.8	319	0.78	55	99.793	1
4023	2.18	6.2	60	0.78	1036	99.981	1
4030	3.28	7.8	177	0.78	120	99.899	1
4032	3.28	7.9	308	0.78	78	98.965	1
4034	3.28	7.8	88	0.78	802	99.916	1
5005	0.97	8.1	294	0.984	669	99.558	1
5006	0.94	8.1	308	0.984	316	99.458	1
5007	0.94	8.4	308	0.984	673	99.805	1
5009	0.94	8.1	308	0.984	692	99.195	1
5010	0.94	8.0	308	0.984	658	99.456	1
5020	2	7.9	77	0.984	1253	99.834	1
5021	2	8.0	77	0.984	1049	99.915	1
5022	2	8.0	77	0.984	1357	99.793	1
5024	2	7.8	58	0.984	2517	99.913	1
5025	3	7.8	61	0.984	1081	99.756	1
5026	3	7.8	61	0.984	1597	99.600	1
5027	3	8.0	61	0.984	1793	99.780	1
5028	3	8.2	61	0.984	1529	99.840	1
5029	3	8.2	61	0.984	1487	99.894	1
5030	1	8.2	54	0.984	3261	99.916	1
5031	2	7.8	57	0.984	2269	99.627	1
5032	1	8.2	82	1.95	1966	99.928	1
5033	0.98	7.8	139	1.95	575	99.947	1
5034	0.98	8.0	284	1.95	232	99.784	1
5035	0.94	7.8	48	1.95	5894	99.330	1
5036	0.94	8.0	82	1.95	2447	99.630	1
5037	0.94	8.1	82	1.95	3467	99.905	1
5038	1	8.0	87	1.01	1669	99.380	1
5039	1	8.0	87	1.01	1607	99.870	1
5040	1	8.1	87	1.01	1633	99.937	1
5041	1	8.1	146	1.01	590	99.939	1
5042	1	8.7	206	1.01	373	99.997	1
5043	1	7.9	304	1.01	130	99.917	1

ID	q	C_S	C_D	ξ	β	R	SS
	GSFM	PPM	PPM	10^9FT/LB	10^4FT^{-2}	%	
5048	1	7.7	124	5.47	1030	99.906	1
5049	1	7.7	205	5.47	526	99.353	1
5053	0.96	8.0	170	0.984	324	99.936	1
5054	0.96	8.0	73	0.984	1766	99.948	1
5055	0.94	8.1	305	0.984	131	99.719	1
5056	0.96	7.8	48	0.984	3901	99.936	1
5057	0.96	7.8	73	0.984	20700	99.994	2
5058	0.96	8.0	73	0.984	25300	99.955	2
5059	0.96	7.9	73	0.984	29520	99.976	2
5060	0.96	8.0	154	0.984	4620	99.939	2
5061	0.96	8.0	328	0.984	1090	99.938	2
5062	0.96	8.2	52	0.984	52000	99.975	2
5063	0.96	8.2	77	0.984	20140	99.825	2
5091	1	8.1	292	0.984	128	99.974	3
5092	0.98	7.4	211	0.984	213	99.864	3
5093	1	7.9	153	0.984	338	99.861	3
5094	1	7.3	79	0.984	1053	99.977	3
5095	1	8.0	83	0.984	1300	99.955	3
5096	1	7.4	88	0.984	1390	99.916	3
5150	1	8.2	173	5.47	575	99.886	1
5151	1	7.9	147	1.95	644	99.923	1
5152	1	7.9	224	1.95	382	99.956	1
5153	1	7.9	124	1.95	879	99.901	1
5154	1	8.1	79	1.37	2179	99.962	1
5155	1	8.4	209	5.47	686	99.986	1
5156	0.98	8.2	207	5.47	527	99.884	1
6111	0.43	11	19.5	1.95	2927		6
6112	0.43	8.7	21.4	1.95	1244		6
6113	0.43	9.6	20.6	1.95	1939		6
6114	0.47	7.5	13.7	1.95	4468		6
6115	0.48	6	17.3	1.95	2149		6
6116	0.34	6	17.5	1.95	1622		6
6117	0.60	6	17.4	1.95	1789		6
6118	0.77	9	22.7	1.95	960		6
6119	0.77	8	21.5	1.95	771		6
6121	0.58	6	24.3	1.95	327		6
6209	1.11	5.4	20.2	1.95	751		6
6210	1.18	7	23	1.95	734		6
6211	0.96	6.1	20.3	1.95	781		6

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ID	q GSFM	C_S PPM	C_D PPM	ξ 10^9 FT/LB	β 10^4 FT^{-2}	R %	SS
6212	0.62	7.5	21.8	1.95	1851		6
6213	0.62	10	21.8	1.95	2889		6
6214	0.58	10	21.8	1.95	1624		6
6215	0.70	8.4	22	1.95	2035		6
6216	0.68	9	22	1.95	2033		6
6217	0.31	5.5	17.6	1.95	2273		6
6218	0.60	6	20.5	1.95	1363		6
6219	0.60	5	22	1.95	635		6
6322	0.77	9.5	21.8	1.95	1430		6
6323	1.04	9	26.4	1.95	818		6
6324	0.97	3	32.4	1.95	102		6
6326	0.77	6.5	20	1.95	619		6
6327	0.74	7.5	22	1.95	1131		6
6328	0.77	8	22	1.95	1243		6
6329	0.77	9.5	29	1.95	570		6
6330	0.86	6.3	21.7	1.95	710		6
6331	0.96	7	25.5	1.95	617		6
6332	0.72	6	21	1.95	1245		6
7003	1	4.4	12.6	5.40	1619	99.975	6
7004	1	4.3	11.5	5.40	2033	100.000	6
7005	1	4.3	22.8	5.40	592	99.999	6
7006	1	9.5	26.2	5.40	1477	99.982	6
7007	1	9.6	43	5.40	599	99.994	6
7008	1	9.3	49	5.40	353	99.997	6
7015	1	2.9	15.4	5.40	3613	99.980	6
7016	1	2.2	13.2	5.40	3780	99.953	6
7017	1	3.3	12.2	5.40	7450	99.953	6
7019	1	5.6	22.8	5.40	1848	99.980	6
7020	1	4.6	38.3	5.40	567	99.968	6
7022	1	4.9	10.2	5.40	7272	100.000	6
7023	1	4.0	67.3	5.40	209	99.998	6

Filter runs with ID numbers beginning with 4 and 5 were also made using the pilot plant. University tap water containing hydrous ferric oxide floc was filtered. The water was prepared by adding iron salts to the water, followed by aeration and mixing. This water will be referred to as iron-bearing water. Filter runs with ID numbers beginning with 4, were made primarily by Iowa State University undergraduate students and are denoted as extra runs. Filter runs with ID numbers beginning with 5 were made by Hall and Hawley (3,10,11).

Filter runs with ID numbers beginning with 7 were conducted using a U.S. Army mobile water purification unit filtering effluent from the lime-soda ash softening process at the Ames, Iowa, municipal water treatment plant. This water contained small amounts of suspended $CaCO_3$ not previously removed by sedimentation, and will be referred to as softened water. The mobile purification unit, referred to by ISU personnel as Miss Purity, is on loan from the U.S. Army Research and Development Laboratories, Fort Belvoir, Virginia. The filter contains 3.5 inch diameter septa and is very similar to the pilot plant. The mobile unit is also equipped with an Erdlator pretreatment unit, a solids-contact-type upflow clarifier. Turbidity units were used as a relative measure of C_S in all filter runs made with the mobile unit.

Filter runs with ID numbers beginning with 2 and 3 were made by Foyster and LaFrenz respectively using a small pressure filter (VHP) with a 6-inch diameter flat septum described in detail by LaFrenz (12). Iron-bearing water was filtered in these runs.

Filter runs with ID numbers beginning with 6 were made at the water treatment plant at Lompoc, California. These filter runs represent the only full-scale plant data included in Table 2. They were actual filter runs made in the production of potable softened water for the City of Lompoc. The diatomite filters at the Lompoc plant are vacuum filters manufactured by BIF, Division of the New York Air Brake Co., Providence, Rhode Island. The septa used are flat. The Lompoc plant is a conventional lime-soda ash softening plant followed by diatomite filters rather than rapid sand filters. It has been described by Lawrence (14). Turbidity units were used as a relative measure of C_S in the Lompoc filter runs.

β INDICES

Table 2 contains a summary of the β indices calculated from the results of approximately 200 filter runs. Included in Table 2 are the unit flow rate (q), solids concentration (C_S), β index (C_D), ξ index (ξ), correlation coefficient of the least squares head loss-time curve in percent (R), and the type of suspended solids (SS).

No correlation coefficient is included in Table 2 for the flat filter cakes (ID numbers beginning with 2,3, or 6). For these runs, β was computed from the K_4 value determined by the original investigator. The equation $\beta = (10)^{-6} g\gamma_w K_4/\nu$ was used to convert K_4 to β. This equation is valid for flat filter cakes, but not for cylindrical filter cakes.

For the cylindrical filter cakes (ID numbers beginning with 1, 4, 5, or 7) β was determined by regression of H on $\ln(1 + R_s\phi x/R_o^2)$. The development of this method for determing β has been described previously (9). The data required for making the calculations (Table 1) are normally collected in a filter run with the exception of values for the dilution rate and for the bulk density of the precoat, γ_p. Values of the dilution rate (δ) were estimated by visual selection of the inflection point of the H versus t curve using the assumption that at this time, δt is approximately 3 (7). Cylindrical septa of 3.5 inch diameter were used in all of these filter runs. In determining the β index, a value of 15 #/ cf was used for γ_p. The IBM 7074-1401 computer system at Iowa State University was used for the regression analyses. The correlation coefficients for the β index of each of the cylindrical cakes are included in Table 2 and are generally well above 99 percent.

Figure 2 illustrates the actual head loss-time data, and the calculated regression head loss-time curves for six of the cylindrical filter cakes (Runs 1203, 4007, 5055, 5060, 5155, 7020). Each curve in Fig. 2 is the curve of best fit determined by regression of H on $\ln(1 + R_s\dot{\phi}x/R_o^2)$. The plotted points represent data collected during the filter run.

Previous diatomite filtration equations assumed that the head loss-time curve (H-t curve) became linear after initial dilution. This is true for flat septa, but not true for cylindrical septa. However, when using 3.5 inch diameter septa, the H-t curve may appear linear for a relatively long time, especially for filter runs with a low body feed concentration. When C_D is low, the thickness of the cake increases slowly, and the effect of the increasing filter area is less noticeable.

The increasing area effect is much more noticeable with 1.0 inch septa (Curve C, Fig. 1), when C_D is high, and in long filter runs after an appreciable cake thickness has formed.

The H-t curves for Runs 7020, 1203, and especially 5060 (Fig. 2) are practically linear after the transition period. Many of the other filter runs analyzed also appeared linear either because the body feed concentration

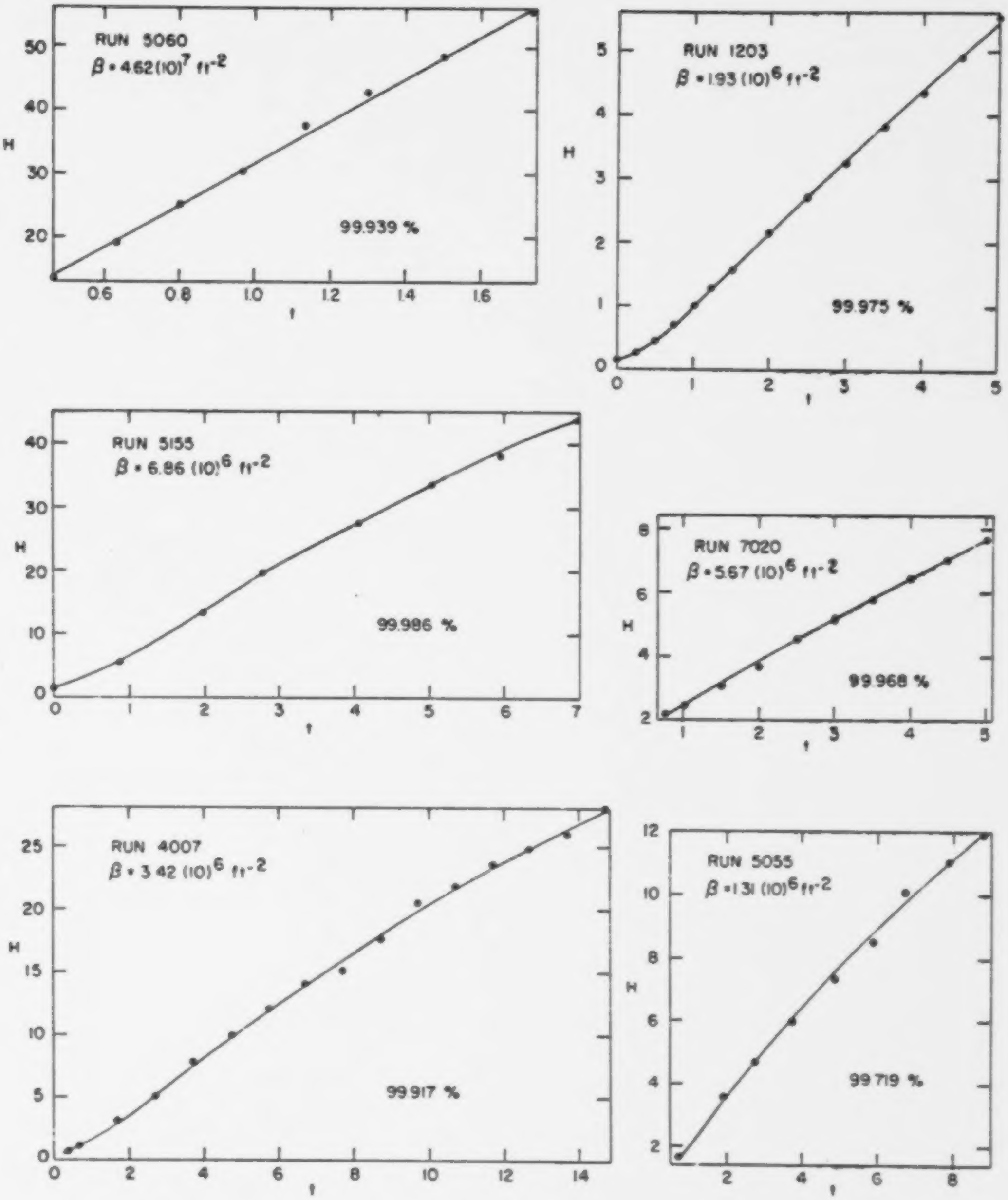

Fig. 2. Actual and regression head loss-time curves for six cylindrical filter cakes (head loss (H) is in ft and time (t) is in hr; corresponding run numbers, β indices, and correlation coefficients in percent are indicated)

was low or the filter run was relatively short. On the basis of linear H-t results such as these obtained with cylindrical septa, it is not surprising that non-applicable linear equations had been used earlier to calculate filter cake resistance coefficients (1,4,5,10,11,15,16).

However, some of the longer runs and runs with high C_D illustrate the effect of increasing area and the inadequacy of the linear equations for cylindrical septa (runs 5055, 4007, and 5155 in Fig. 2). The filter runs summarized in Table 2 verify the filtration head loss equations in Table 1 for flat (Equation 4) and cylindrical septa (Equation 2). They demonstrate that the β index remains constant during a filter run as long as q, C_S, and C_D remain constant.

PREDICTION EQUATIONS

The β index representing the filter cake resistance is a function of the concentration of suspended solids (C_S) and body feed diatomite (C_D) in the water, and of the filter aid resistance index (ξ). In general, a design engineer will need to be able to predict the changes in filter cake resistance which will occur due to changes in C_S, C_D, and in the filter aid used in subsequent filter runs. For this reason, a β prediction equation was developed in this study in the general form:

$$\beta = 10^{b1} \, (C_S/C_D)^{b2} \, C_D^{\,b3} \, \xi^{b4} \tag{6}$$

where b_1, b_2, b_3, and b_4 are exponents determined empirically.

In this study, the ratio of C_S/C_D (the relative proportions of suspended solids and diatomite in the filter cake) was used for convenience with C_D and ξ to serve as independent variables. The ratio of C_S/C_D is the primary variable affecting cake resistance and had been used in earlier cake resistance prediction studies (1,5,10,11,15,16). It was found that use of the additional variable C_D improved cake resistance prediction attempts (7). Furthermore, the tabulation of data from most runs listed values for C_D and C_S/C_D. Thus, the use of the β-prediction equation in this form was most convenient. The variables could have been separated and the β-prediction equation written in the following form:

$$\beta = 10^a \, C_s^{\,b} \, C_D^{\,c} \, \xi^d$$

The general prediction equation (6) can be made linear with a log transformation leading to:

$$\log \beta = b_1 + b_2 \log (C_S/C_D) + b_3 \log C_D + b_4 \log \xi \qquad (7)$$

The coefficients b_1, b_2, b_3, and b_4 can be determined by linear regression taking log β as the dependent variable and log (C_S/C_D), log C_D, and log ξ as the independent variables.

In some cases, b_3 or b_4 or both may be zero. For example, if the prediction equation was developed from a group of filter runs in which the same filter aid was used, then ξ would be the same for all the filter runs, and log ξ would not be a variable. In such a case, log ξ should be dropped ($b_4 = 0$).

Also, if C_S is constant for a group of filter runs then C_S/C_D and C_D would not be independent variables. In such a case, log C_D should be dropped ($b_3 = 0$). If C_S is constant and the same filter aid was used for a group of filter runs, then log C_D and log ξ should both be dropped and both b_3 and b_4 would be zero.

When b_3 and b_4 are both zero in Equation 6 ($b_3 = b_4 = 0$), the prediction is similar to the previously used method of predicting cake resistance by means of a log-log plot of K_4 versus C_S/C_D (1,2,3,5,10,11,15,16). In that case, the prediction equation is of the form:

$$\beta = 10^{b1} (C_S/C_D)^{b2} C_D^{\ 0} \xi^0 = 10^{b1} (C_S/C_D)^{b2} \tag{8}$$

A summary of the β-prediction equations determined from the results of the filter runs summarized in Table 2 is presented in Table 3. Several of the prediction equations are of the form shown in Equation 8 ($b_3 = b_4 = 0$).

In Table 3, the group of runs used to determine each prediction equation is indicated. For example, the β-prediction equation for Runs 2009, 2019-2026 was determined from the data of Run 2009 and the Runs inclusively listed from Run 2019 to Run 2026 in Table 2. The correlation coefficient (R,%) for each β-prediction equation is indicated.

Filter runs were separated into groups for the determination of the β-prediction equations on the basis of filter used, suspensions filtered, and filter aid grade used. The same filter aid grade was used in all filter runs of each group except for the five groups that have a prediction equation that contains ξ (ξ in Tables 2 and 3). The same suspension of solids (same SS number, Table 2) was filtered and the same filter was used in each group of filter runs in Table 3 except for the group made up of Runs 6111-7023, which includes both Lompoc filter runs and Ames (mobile unit) filter runs. Softened waters from the two municipal water plants were filtered in this group. Although it is not apparent in Table 2, the filtrability of the water filtered in Runs 310030-312100 was not the same as the filtrability of the water filtered in Runs 302020-309160. In the former group of runs, a small quantity of Cu^{++} was added to the water to aid in the oxidation of Fe^{++} to Fe^{+++}, and resulted in significantly different water filtrability. Therefore, these groups of data were analyzed separately in Table 3.

The β-prediction equations resulting from data collected in filter runs filtering iron-bearing water at the same iron concentration using the same filter aid gave some of the highest R values (prediction equations for Runs 2010-2013; 302020-302800; 305020-305160; 309020-309160; 310030-310160; 312020-312100; 5038-5043; 5053-5056; 5057-5063; 5091-5096). These β-prediction equations have the form of Equation 8. In practice, this type of prediction equation would probably find more application for iron removal from ground water supplies because the iron concentration of the raw water would probably remain constant over long periods of time.

Figure 3 shows a number of plots of observed values of log β versus calculated values of log β. The observed values of log β for a given run were taken from Table 2 and represent the actual value of β calculated from the run data. The so-called calculated values of log β were calculated for the data of each run using the appropriate β-prediction equation from Table 3.

One of the lowest values of R (86.2%) is the one for the prediction equation developed from data from Runs 6209-6219 shown in Fig. 3. These

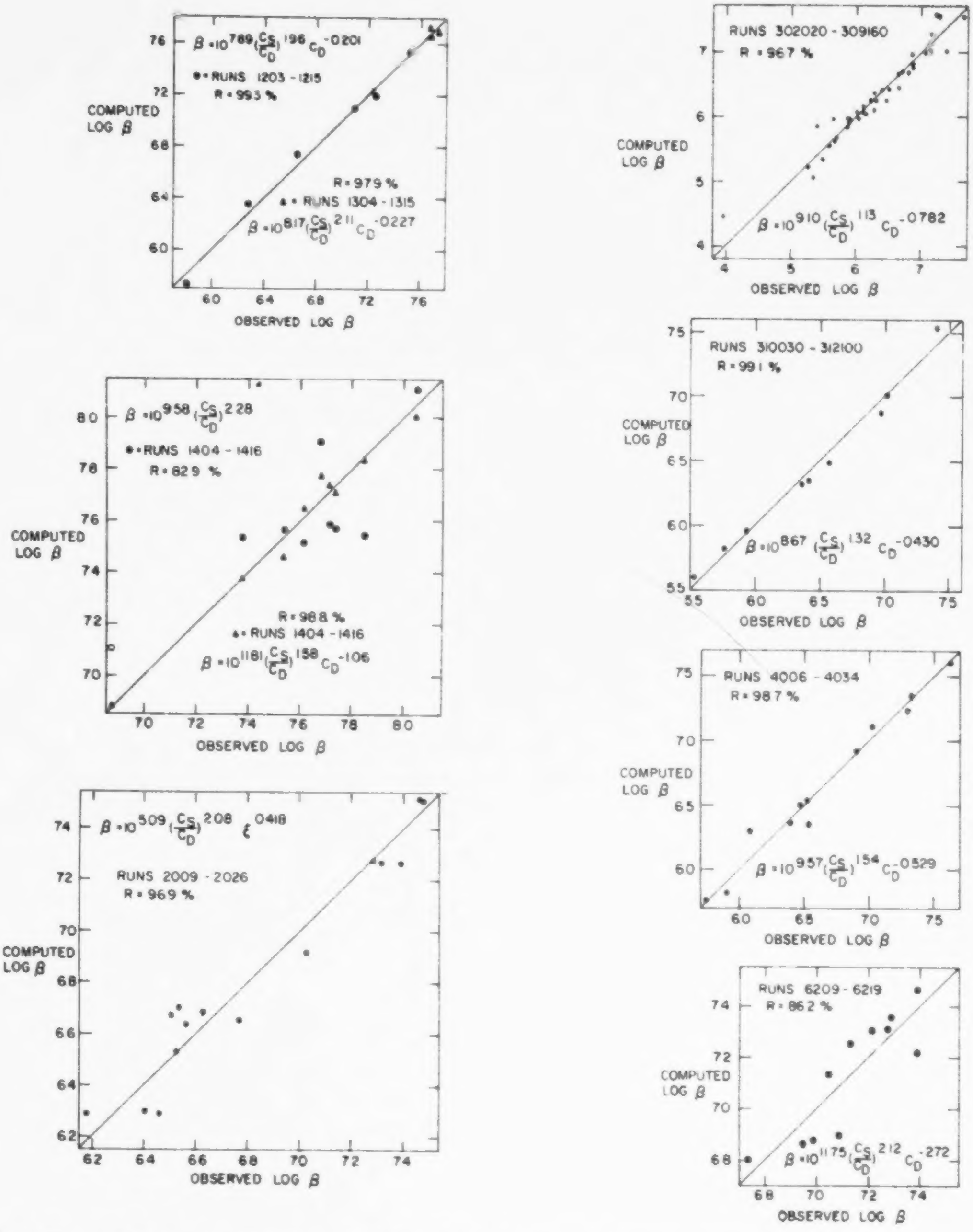

Fig. 3. Plots of computed log β (using β-prediction equation) versus observed log β (Table 2) for some of the run groups in Table 3 (inclusive filter run numbers, prediction equation, and correlation coefficient in percent are indicated for each plot)

Table 3. SUMMARY OF β-PREDICTION EQUATIONS

RUNS	β-PREDICTION EQUATION	R,%
1203-1215	$\beta = 10^{7.26}(C_S/C_D)^{2.00}$	99.2
	$\beta = 10^{7.59}(C_S/C_D)^{1.96}C_D^{-0.201}$	99.3
1304-1315	$\beta = 10^{7.73}(C_S/C_D)^{2.38}$	97.8
	$\beta = 10^{8.17}(C_S/C_D)^{2.11}C_D^{-0.227}$	97.9
1203-1315	$\beta = 10^{3.43}(C_S/C_D)^{1.96}C_D^{-0.254}\xi^{0.491}$	99.6
1404-1416	$\beta = 10^{9.58}(C_S/C_D)^{2.28}$	82.9
	$\beta = 10^{11.81}(C_S/C_D)^{1.58}C_D^{-1.06}$	98.8
2010-2013	$\beta = 10^{8.90}(C_S/C_D)^{1.92}$	99.0
2009, 2019-2026	$\beta = 10^{8.98}(C_S/C_D)^{2.29}$	96.6
2009-2026	$\beta = 10^{5.09}(C_S/C_D)^{2.08}\xi^{0.418}$	96.9
302020-302800	$\beta = 10^{8.72}(C_S/C_D)^{2.14}$	98.3
303020-303300	$\beta = 10^{8.24}(C_S/C_D)^{1.67}$	97.4
304020-304160	$\beta = 10^{8.34}(C_S/C_D)^{1.96}$	93.5
305020-305160	$\beta = 10^{8.43}(C_S/C_D)^{1.79}$	99.7

RUNS	β-PREDICTION EQUATION	R,%
309020- 309160	$\beta = 10^{8.66}(C_S/C_D)^{1.76}$	99.9
310030- 310160	$= 10^{8.75}(C_S/C_D)^{2.02}$	99.9
312020- 312100	$\beta = 10^{8.05}(C_S/C_D)^{1.47}$	99.7
302020- 309160	$\beta = 10^{8.36}(C_S/C_D)^{1.79}$	94.8
	$\beta = 10^{9.10}(C_S/C_D)^{1.13}C_D^{-0.782}$	96.7
310030- 312100	$\beta = 10^{8.24}(C_S/C_D)^{1.65}$	98.9
	$\beta = 10^{8.67}(C_S/C_D)^{1.32}C_D^{-0.430}$	99.1
4006-4034	$\beta = 10^{9.23}(C_S/C_D)^{2.14}$	97.4
	$\beta = 10^{9.57}(C_S/C_D)^{1.54}C_D^{-0.529}$	98.7
5005-5031	$\beta = 10^{7.80}(C_S/C_D)^{0.618}$	89.9
5032-5037	$\beta = 10^{9.33}(C_S/C_D)^{1.95}$	97.7
5038-5043	$\beta = 10^{9.26}(C_S/C_D)^{1.98}$	99.9
5053-5056	$\beta = 10^{9.05}(C_S/C_D)^{1.88}$	99.9
5057-5063	$\beta = 10^{10.41}(C_S/C_D)^{2.10}$	99.6
5091-5096	$\beta = 10^{9.05}(C_S/C_D)^{1.89}$	98.5

RUNS	β-PREDICTION EQUATION	R, %
5150-5156	$\beta = 10^{8.70}$ ([illegible]$_S$/[illegible]$_D$)$^{1.4}$[illegible]	95.[illegible]
	$\beta = 10^{7.30}$ ([illegible]$_S$/[illegible]$_D$)$^{1.61}$ $\xi^{0.}$[illegible]	96.2
5032-5056 5150-5156	$\beta = 10^{7.09}$ ([illegible]$_S$/[illegible]$_D$)$^{1.}$[illegible] $\xi^{0.}$[illegible]	[illegible]
6111-6121	$\beta = 10^{8.14}$ ([illegible]$_S$/[illegible]$_D$)$^{2.41}$	80.[illegible]
	$\beta = 10^{11.15}$ ([illegible]$_S$/[illegible]$_D$)$^{1.6}$[illegible] [illegible]$^{-1.59}$	[illegible]6.2
6209-6219	$\beta = 10^{8.04}$ ([illegible]$_S$/[illegible]$_D$)$^{1.8}$[illegible]	[illegible]
	$\beta = 10^{11.75}$ ([illegible]$_S$/[illegible]$_D$)$^{1.12}$ [illegible]$^{-1.72}$	[illegible]
6322-6332	$\beta = 10^{7.73}$ ([illegible]$_S$/[illegible]$_D$)$^{1.67}$	9[illegible]
	$\beta = 10^{9.32}$ ([illegible]$_S$/[illegible]$_D$)$^{1.56}$ [illegible]$_D^{-1.26}$	[illegible]
6111-6332	$\beta = 10^{10.20}$ ([illegible]$_S$/[illegible]$_D$)$^{1.4}$[illegible] [illegible]$_D^{-1.56}$	9[illegible].2
7003-7023	$\beta = 10^{}$[illegible]$^{.04}$ ([illegible]$_S$/[illegible]$_D$)$^{1.}$[illegible]	[illegible]
	$\beta = 10^{9.}$[illegible] ([illegible]$_S$/[illegible]$_D$)$^{0.0}$[illegible] [illegible]	9[illegible]
6111-7023	$\beta = 10$[illegible] ([illegible]$_S$/[illegible]$_D$)$^{0.}$[illegible] [illegible] $\xi^{0.6}$[illegible]	[illegible]

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runs were made at Lompoc, California using filter number 2. R should be above 90 percent and preferably above 95 percent for good β prediction. However, as demonstrated by the results in Table 3, most of the R's are above 95 percent.

It is reasonable to assume that β is chiefly a function of C_S/C_D, and, therefore, that the use of Equation 8 would normally result in fairly high R values. If this ratio were constant for a group of filter runs, it would seem that the resulting filter cakes would have the same characteristics, and thus, the same β index. For example, if a filter run were repeated under the same conditions except that C_S and C_D were doubled, the ratio C_S/C_D would be the same. It would be reasonable to assume that the resulting filter cake would be the same as the first, but formed twice as fast.

However, the use of Equation 8 as a prediction equation did not result in high R's for some of the waters filtered. Relatively high R's were obtained for water containing kaolinite (Runs 1203-1215; 1304-1315) and for iron-bearing water (Runs 302020-309160; 310030-312100; 4006-4034) when C_S was not the same for each group of filter runs. However, relatively low R's resulted for water containing montmorillonite (Runs 1404-1416) and softened water (Runs 6111-6121; 6209-6219; 6322-6332; 7003-7023). Relatively low correlation was obtained previously with water containing montmorillonite when trying to predict the variation of cake resistance (as represented by K_4) with C_S/C_D by use of a log-log plot of K_4 versus C_S/C_D (15,16).

To improve the β prediction in these runs, the β-prediction equation was used in the following form ($b_4 = 0$ in Equation 6):

$$\beta = 10^{b_1} (C_S/C_D)^{b_2} C_D^{b_3} \qquad (9)$$

The use of Equation 9 made possible substantial improvement in β prediction for softened water and for water containing montmorillonite. The reliability of the β-prediction equation, as measured by R values, increased from 82.9 percent using Equation 8 to 98.8 percent using Equation 9 for developing a prediction equation from Runs 1404-1416. This increase in β prediction is also illustrated by the plot of computed log β versus observed log β for the two prediction equations for these runs (Fig. 3).

The use of the prediction equation in the form of Equation 9 also improved β prediction, but not as significantly, for iron-bearing water (Runs 302020-309160; 310030-312100; 4006-4034) and for water containing kaolinite (Runs 1203-1215; 1304-1315).

An explanation of the different degrees of improvement in β prediction for different waters resulting from the use of prediction equations in the form of Equation 9 rather than Equation 8 is not readily apparent. Possibly, the use of β index, rather than specific cake resistance based on weight of diatomite (z_c), is a major contributing factor. However, a true value of z_c is difficult to determine especially when using cylindrical septa (9).

If accurate values of C_S, C_D and γ_p were known, and all the hypotheses assumed in the derivation of Equation 2 were true for a particular run used for the determination of β index, an accurate value of z_c could be determined from the β index. This is rarely the case, and therefore, β is not ordinarily a true measure of cake resistance and this is the reason it is referred to as an index of cake resistance.

However, the β-index is an excellent index of cake resistance as demonstrated by the very high R values in Table 2. A value of β index can be determined that accurately describes the head loss-time curve for a filter run even when using estimated values of γ_p, when using turbidity units in place of C_S (turbidity units are used in place of C_S for filter runs with ID numbers beginning with 1, 6, and 7), and possibly when the solids do increase cake thickness appreciably. Such successful applications make the use of β index practical. The important thing is that the use of a β-prediction equation in the form of Equation 9 rather than of Equation 8, tremendously increases the accuracy of β index prediction in some cases.

If the use of β index rather than z_c is the primary reason for the differences, then the C_D term in the prediction equation (Equation 9) serves primarily as a factor that compensates for inaccuracies in β relative to z_c.

The swelling property exhibited by montmorillonite when placed in water may be a factor contributing to inaccuracies in β determination for waters containing this suspended solid. The swelling of this clay, if it occurs in a filter cake, would increase the thickness of the filter cake and result in an error in the determination of β. This swelling property might be a significant factor in the explanation of the poor correlation of log K_4 with log (C_S/C_D) for Wyoming bentonite (15,16).

The poorer correlation, obtained with the β-prediction equation in the form of Equation 8 with water containing montmorillonite and for softened water may be a result of using turbidity in place of C_S in the correlation. Turbidity is a measure of the scatter of light beams passed through the water, and is not normally considered a good measure of suspended solids concentration (C_S). Also, turbidities of the unfiltered water were normally less than 10 for the softened water, and the accurate measurement of low turbidity is difficult.

The C_S/C_D exponent in the β-prediction equation like Equation 9 for Runs 7003-7023 is only 0.0361. This is an indication that the variation in β for these runs was largely due to the variation in C_D and practically independent of C_S. This is a strong indication that the turbidity values were probably in error.

Low R values for the prediction equations derived from the Lompoc filter runs (Runs 6111-6332)were undoubtedly the combined result of several factors; primarily, the fact that the Lompoc plant was designed and built for the production of potable water for the City of Lompoc and not for research purposes. Measurement of the actual flow rate, turbidity, and body feed concentration for each of the filters, although adequate for plant operation, was not adequate to the accuracy desired for research purposes. Turbidity and body feed concentration could not be determined separately for each filter, and therefore, concentrations in the total flow stream had to be used. It was noticed in some instances that the rate of increase of cake thickness was not the same on all three filters. Therefore, the flow rate, turbidity, and body feed concentration were not the same for all three filters.

The exponent of C_D is negative for all prediction equations that contain the C_D term. This is an indication that the variation of β index is more affected by changes in C_D than in C_S.

Some of the β-prediction equations in Table 3 contain ξ (Equation 6). The use of this form of the prediction equation is not recommended because of the ξ index, although a good index of filter aid hydraulic characteristics, is not an adequate index of the filtering characteristics of filter aids (6,8). It is more desirable to determine a separate β-prediction equation for each grade of filter aid which is being considered for plant operation. However, good β-prediction results can be obtained if the correlation coefficient is high and no attempt is made to predict a β index for a filter aid grade that was not included in the pilot filter runs from which the prediction equation exponents were determined.

The prediction equations that include ξ were determined because they give an indication of the variation of β index with ξ index (i.e., variation of cake resistance with precoat filter aid resistance). The exponent of ξ for every one of these equations is less than 1. This indicates that changes in filter aid resistance result in relatively smaller changes in filter cake resistance. This result was demonstrated with iron-bearing water in Runs 5032-5056; 5150-5156 (5,10). The prediction equations demonstrate the same result for water containing kaolinite (Runs 1203-1315) and for softened water (Runs 6111-7023).

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SUMMARY AND CONCLUSIONS

Approximately 200 diatomite filter runs were analyzed using recently developed diatomite filtration equations (Equations 2 and 4) (7,9). The different types of water filtered in these filter runs include iron-bearing water, clay-bearing water (kaolinite or montmorillonite), and lime-soda ash softened water.

The following conclusions are indicated:

1. The filtration head loss equations (Equations 2 and 4) give excellent results in describing the head loss-time relationships for flat and cylindrical filter cakes.
2. The form of the β index prediction equation used in this study can be used to describe with reasonable accuracy the variation of cake resistance with the concentration of solids (C_S) and concentration of body feed (C_D), and, in some cases, the precoat resistance index (ξ index).
3. The use of a β-index prediction equation in the form $\beta = 10^{b1} (C_S/C_D)^{b2} C_D^{b3}$ rather than one of the form $\beta = 10^{b1} (C_S/C_D)^{b2}$, significantly increases the accuracy of β prediction in some cases. This is especially true for water containing montmorillonite clay and for lime-soda ash softened water.
4. Variation of the ξ index results in correspondingly less variation in the β index.

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PART V

OPTIMUM DESIGN AND OPERATION OF DIATOMITE FILTRATION PLANTS

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Progress Report

OPTIMUM DESIGN AND OPERATION OF DIATOMITE FILTRATION PLANTS

by

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United States Public Health Serivce
Division of Water Supply and Pollution Control
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OPTIMUM DESIGN AND OPERATION OF DIATOMITE FILTRATION PLANTS

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January 3, 1966

BACKGROUND

Alternative Costs

Traditionally, sanitary engineering processes have been designed on the basis of the application of the current "art" to provide a plant which will operate at a cost that the consumer is willing to pay. Cost comparisons which are made have frequently been restricted to comparisons of two or more alternate methods of applying the "art". In practice, therefore, it is doubtful that many cost comparisons in the past have successfully led to design of plants which would operate at least cost for that type of plant. In recent years, however, there has been increasing interest in and ability to produce adequate mathematical models to describe various sanitary engineering processes. With the use of high-speed computers, it has become possible to optimize all the variables which affect costs to provide truly least cost plant design and operation.

According to the recent Task Group Report on Diatomite Filtration (8): "As far as the committee has discovered, no diatomite or rapid sand plant has yet been designed to operate in its most economical range, although several installations may approach this condition." One of the main reasons for this lack of optimum economical design is that making accurate cost predictions for varying operating conditions is very difficult. Total cost of production is a very complex function of the several variables involved, and accurate cost predictions have not generally been possible. Variables that influence the cost of diatomite filtration include: quantity of water needed, characteristics of the raw water, characteristics of the filter aid, characteristics of the equipment (type of installation), flow rate, body feed concentration, terminal head loss, etc.

Figure 1 represents a schematic diagram showing the costs of five alternatives of design in the form of a two-dimensional plot. It is rarely possible to draw a meaningful two-dimensional plot to show the variation in cost with a single parameter that includes the effects of all of the other parameters that affect costs. However, Fig. 1 is useful for illustrative purposes if we assume that all cost parameters are represented by the single alternative shown by the abscissa.

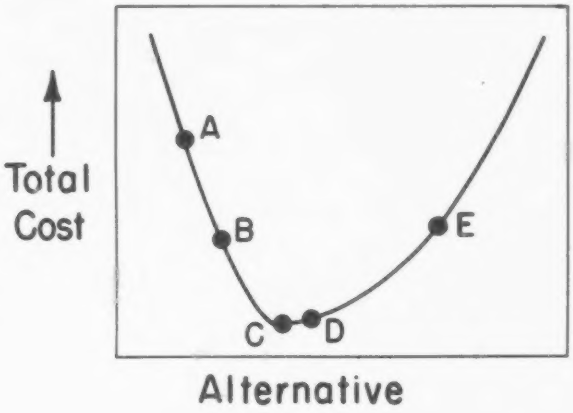

Fig. 1. Schematic diagram of total cost of water production for different alternatives

Point C in Fig. 1 represents the value of the variables resulting in least cost design. However, in some cases it may be more practical to design at some point near the least cost point, such as point D. A diatomite filtration plant can rarely be operated under a particular rigid set of operating conditions because of variations in the influent quality, accuracy of body feeding equipment, etc. Since the hypothetical cost curve in Fig. 1 is steeper to the left of point C, small changes in operating conditions could shift the point of operation to the left resulting in significant increase in costs. But, if the plant were designed to operate at point D, cost of production would not be so sensitive with respect to small changes in operating conditions.

The desirable approach in design is to evaluate the effect of all variables in several alternatives to provide a more accurate picture of cost variation. The greater the number of combinations of the variables considered, the more accurately the cost picture will be known. Manually, it is impractical to make more than a few comparisons because of the large number of calculations necessary. However, with the use of a digital computer, as many comparisons as desired can be made in a relatively short time if a suitable computer program is available.

Objective

The primary objective of this study was the development of a digital computer program for use in designing diatomite filtration plants to produce filtered water of requisite quality at least cost. To achieve the objective, it was necessary to be able to predict operating costs for different combinations of filter aid grade, flow rate, type and concentration of suspended solids, terminal head loss, body feed concentration, and different types of equipment (pressure or vacuum filters, degree of automation, etc.). Preludes to the development of the program included:

1. Development of theoretical diatomite filtration equations that describe the head loss-time relationship of diatomite filter cakes formed on flat and cylindrical septa(3).

2. Development of empirical equations for predicting changes in filter cake resistance for corresponding changes in suspended solids concentration, body feed concentration, and possibly filter aid grade(4).

Equations

The development of the theoretical filtration equations and the empirical prediction equations used in this study were presented previously (2,3,4). The theoretical filtration equations are summarized for easy reference in Table 1. As presented, they are valid for use with any consistent set of units - such as ft.-lb.-sec. or cm-gm-sec. A convenient set of English units is ft.-lb.-hr. The dimensions of the terms used in the filtration equations are indicated in brackets.

Empirical filter cake resistance or β-prediction equations have been developed on the basis of results from nearly 200 filter runs (2,4). It was found that a prediction equation of the general form of Equation 6 gave excellent correlations.

$$\beta = 10^{b_1} (C_S/C_D)^{b_2} C_D{}^{b_3} \xi^{b_4} \qquad (6)$$

Whenever a diatomite filtration plant is to be designed for a given application, the exponents of Equation 6 should be determined

Table 1. DIATOMITE FILTRATION EQUATIONS

(Any Septum) $$H_p = q\nu\xi w/g \qquad (1)$$

(Cylindrical Septum) $$H_c = \frac{R_s\sigma}{\phi}\ln\left(1 + \frac{R_s\phi x}{R_o^2}\right) \qquad (2)$$

$$L = \sqrt{R_o^2 + R_s\phi x} - R_s \qquad (3)$$

(Flat Septum) $$H_c = \sigma x \qquad (4)$$

$$L = L_p + \frac{\phi x}{2} \qquad (5)$$

$\sigma = q^2\nu\beta C_D/g$ $[LT^{-1}]$

$\phi = 2q\gamma_w C_D(10)^{-6}/\gamma_p$ $[LT^{-1}]$

$x = t - (1 - e^{-\delta t})/\delta$ $[T]$

$\delta = Q/V_f$ $[T^{-1}]$

$R_o = R_s + L_p$ $[L]$

$L_p = w/\gamma_p$ $[L]$

Symbol	Meaning
A_s	Septum area $[L^2]$
β	Filter cake resistance index or β index $[L^{-2}]$
C_D	Body feed concentration, ppm by weight
C_S	Suspended solids concentration, ppm by weight
δ	Dilution rate, theoretically Q/V_f $[T^{-1}]$
g	Gravity constant $[LT^{-2}]$
γ_p (γ_c)	Bulk density of precoat (filter cake) $[FL^{-3}]$
γ_w	Density of water
H_p (H_c)	Head loss through precoat (filter cake) $[L]$

Symbol	Meaning
L_p (L_c)	Thickness of precoat (filter cake) $[L]$
L	$L_p + L_c$ $[L]$
ν	Kinematic viscosity $[L^2T^{-1}]$
Q	Flow rate $[L^3T^{-1}]$
q	Flow rate per unit septum area (filtration rate, Q/A_s) $[LT^{-1}]$
R_s	Radius (outer) of septum $[L]$
t	Time $[T]$
w	Precoat weight per unit area $[FL^{-2}]$
ξ	Filter aid resistance index or ξ index $[F^{-1}L]$
z_c	Specific cake resistance based on weight of diatomite in filter cake $[F^{-1}L]$

from several pilot filter tests made at the site (2,4). When the same filter aid grade is used in the pilot tests as will be used in the prototype plant, ξ should be dropped from the prediction equation ($b_4 = 0$). Also, if C_S is constant for the pilot plant tests, the term $C_D^{b_3}$ should be dropped from the prediction equation ($b_3 = 0$) because, in this case, C_S/C_D and C_D are not independent.

A few of the typical β-prediction equations for various types of suspended solids are summarized in Table 2. More complete data have been presented (2,4).

Table 2. Brief List of β-Prediction Equations

Type of Suspension	b_1	b_2	b_3	b_4	Used in Example Job No's.
Iron-prepared from ferrous sulfate	9.33	1.95	0	0	1,2
Iron-prepared from ferrous sulfate	6.09	1.87	0	0.335	3,4,5
Kaolinite clay	3.43	1.96	-0.254	0.491	6,7
Montmorillonite clay	11.81	1.58	-1.06	0	8
Lime-softened water, Lompoc, Calif.	10.2	1.43	-1.86	0	9
Lime-softened water, Lompoc and Ames	3.23	0.914	-1.25	0.637	10,11,12,13

DESIGN APPROACH

A computer program has been developed as a part of this study for use in determining the optimum operating conditions for a specific type of plant filtering a particular water using a specified grade of filter aid. This program has been named POPO (Program for Optimization of

Plant Operation). POPO determines the optimum combination of filtration rate, body feed concentration and terminal head loss by simply computing costs of filtration for any desired number of different combinations and choosing the ten most economical. Costs resulting from use of different types of equipment and different grades of filter aid can be compared by making appropriate changes in the computer input data, repeating the optimization process for each, and comparing the results.

In subsequent discussion, for convenience, a combination of flow rate (q), body feed concentration (C_D), and terminal head loss (H) will be abbreviated as an order set of three numbers enclosed in double parentheses ((q, C_D, H)) -- e.g., the combination q = 1 gsfm (gpm/ft^2), C_D = 30 ppm, and H = 130 ft of water would be ((1, 30, 130)).

Filtration costs are made up of the first cost of the plant and the operating costs. Plant first cost includes the cost of filters, body feeding equipment, pumps and piping, filter building, and all other necessary equipment. Operating costs include costs of power, labor, maintenance, diatomite and backwashing. There are other incidental costs which contribute to the total cost of filtration, such as administration, insurance, etc., but these costs do not ordinarily vary with the choice of operating conditions.

The cost of filtration depends primarily on the filtrability of the water. Filtrability in this paper is defined as the capability or relative ease of being filtered and is measured by the resistance of filter cakes formed when filtering the water. A water that typically results in filter cakes of high resistance or requires relatively large amounts of body feed to form incompressible cakes has a low filtrability (high β index). On the other hand, a water that typically results in filter cakes of low resistance or requires relatively small amounts of body feed to form incompressible cakes has a high filtrability (low β index). Effluent quality or the amount of solids passing through the filter cake is not a factor in this definition. Throughout this development, it is assumed that the effluent quality is acceptable for each combination ((q, C_D, H)) being considered.

The use of POPO in the design of a diatomite filtration plant involves:

1. The accumulation of cost data needed for computation of filtration costs.

2. The determination of the filtrability of the water to be filtered by running pilot plant tests at the source (2,4). Sufficient pilot plant filter runs should be made to determine β-index prediction equations for each type of filter aid to be considered and for each suspended solids type and range of concentration to be filtered.

3. The use of POPO to determine the optimum operating conditions ((q, C_D, H)) for each type of plant and each type of filter aid being considered. The use of POPO is explained elsewhere (1,2).

POPO is designed to determine the optimum combination ((q, C_D, H)) for a particular type of plant filtering a water of known filtrability using a particular filter aid. The filtrability is represented by the β index prediction equation for the particular filter aid. For each combination ((q, C_D, H)), POPO follows the procedure indicated below:

1. Computes the filter septum area needed by dividing the total plant flow by the unit flow rate ($A_S = Q/q$).

2. Predicts β index by using an appropriate β index prediction equation.

3. Computes the length of filter run and the terminal filter cake thickness, including precoat thickness, using the diatomite filtration equations. The length of filter run is the time during the filter cycle that the filter is in the filtering operation, i.e., it does not include time of precoating and time of backwashing.

4. Computes the first cost, operating costs, and total cost of filtration per million gallons as described in the next section.

5. Compares the resulting total filtration cost with total costs computed previously for other combinations. If it is one of the ten cheapest combinations for which costs have been computed, the results are stored for subsequent output.

Then, after costs have been computed and compared for all the specified combinations which the designer requests POPO to analyze, the results for the ten cheapest combinations are printed out.

COST ASSUMPTIONS AND METHODS OF COMPUTATION

First Cost

In developing POPO, it was assumed that the first cost of a diatomite filtration plant is primarily dependent on the filter area needed and the flow capacity required. Since the filter area needed is equal to the total flow divided by the unit flow rate (Q/q), plant first cost is dependent on q. A plant of a given filter area, say 1000 sq ft, would cost more if it treated a larger flow because the pumps and piping, body feeding equipment, and other equipment would have to be larger to handle the larger flow.

A plot of plant first cost in dollars per square foot versus filter area (log scale) is shown in Fig. 2. The cost information plotted includes cost information obtained from filter manufacturers and some existing filtration installations, and cost estimates made in 1960-61 by LaFrenz (5).

This cost information was accumulated and is used in this paper ONLY for the purpose of DEMONSTRATING the use of POPO, and should not be used in the design of an actual filtration plant. Costs can vary tremendously depending on the type of plant, location, etc., as demonstrated by Fig. 2. Costs can also vary with time. The more accurate and current the data used by the consultant to prepare a first cost-area curve similar to the curve in Fig. 2, the better will be the resulting cost optimization.

The consultant may wish to use several cost-area curves by developing cost data for pressure filters with flat and cylindrical septa and for vacuum filters with flat and cylindrical septa. POPO can be used with different cost curves of this type. After first cost-area curves have been prepared for a particular installation, the first cost of plants of

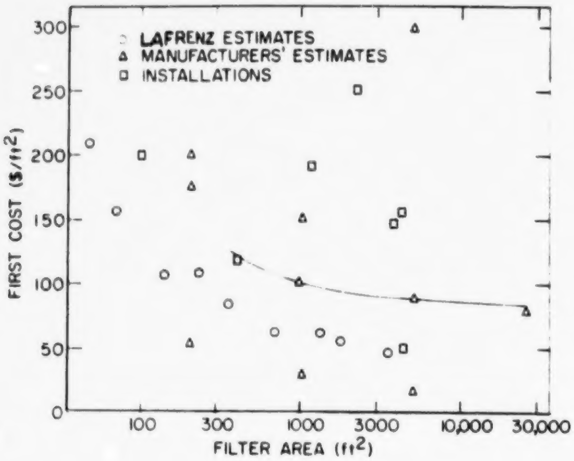

Fig. 2. Semilog plot of plant first cost per unit filter area versus filter area (log scale) for cost estimates made by LaFrenz (5) and filter manufacturers' representatives and for cost information on some existing installations

various areas can be determined from this curve. In calculating first cost as a part of plant operating costs, POPO amortizes the plant first cost over the life of the plant using an interest rate, plant life, and salvage value specified by the designer and included in the POPO input data.

Labor and Maintenance Cost

In developing POPO, it was assumed that both the labor and maintenance required in the plant operation depend primarily on the size of the plant (similar to plant first cost assumption), i.e., filter area and capacity. For this reason, labor and maintenance costs are combined and computed in the same way as plant first costs.

Figure 3 illustrates the plot of combined monthly labor and maintenance costs per unit of filter area versus area (log scale) using cost data for various installations and estimates made by manufacturers' representatives. Most of the points shown in Fig. 3 are representative of automatic backwashing filter plants. There seems to be a definite trend towards automatic backwash plants for diatomite filter installations, for which less operational attendance is needed.

Figure 3, like Fig. 2, was prepared ONLY for the demonstration of the use of POPO, and SHOULD NOT BE USED when designing an actual installation. Actual estimates of monthly labor and maintenance costs should be made and a cost-area curve similar to the one shown in Fig. 3 prepared for each installation to be designed.

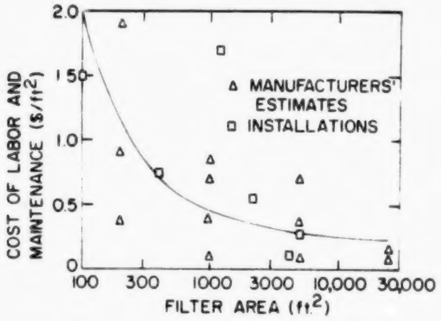

Fig. 3. Semilog plot of monthly labor and maintenance cost per unit filter area versus filter area (log scale) for cost estimates supplied by manufacturers and for cost information on some existing installations

Diatomite Cost

The cost of diatomite is computed as simply the total weight of diatomite used in filtration times the cost per unit weight. The total weight of diatomite used includes the diatomite used for precoating and for body feed. The weight of body feed is found by multiplying the weight of water produced by the weight fraction of body feed used. The weight of precoat used per filter cycle is equal to the filter area times the precoat weight applied per unit area. Diatomite cost per unit volume of water produced is a function of body feed concentration and the length of filter run.

Power Cost

The cost of power is computed on the basis of a unit cost per kilowatt-hour (kwh). It is realized, of course, that power costs usually consist of a demand charge and an energy charge. Methods of computing these charges vary from one location to the next. The energy charge is usually computed on the basis of a decreasing unit cost per kwh for successive increments of energy -- i.e., 4 cents per kwh for the first 400 kwh, 3.5 cents per kwh for the next 500 kwh, etc.

In developing POPO, it was assumed that the energy needed to pump the water through the filter is a small portion of the total energy needs of the water utility installation. Energy may also be needed for heating, pumping the water into the distribution system, booster pumps, well pumps, etc. These other energy needs, for the most part, are independent of the terminal head loss through the filters, and therefore, are excluded from energy cost computations made for the purpose of plant optimization.

It is further assumed that the total energy needs are large enough that the lowest unit cost per kwh can be used to compute the cost of energy for filtering. The demand charge is not included in the power cost calculation because of the many different ways it is computed, and because it is usually a fairly small portion of the total power bill.

The validity of these assumptions will depend on the particular installation. However, this method of power cost computation will generally be applicable to different types and sizes of filtration plants in different locations.

The energy needed per month for filtering is computed on the basis of pumping the quantity of water produced per month against the terminal head loss -- i.e., the weight of water produced per month times the terminal head loss divided by an assumed overall efficiency of energy conversion. This quantity is converted to kwh and multiplied by the unit cost per kwh to obtain monthly power cost.

There is a potential power cost savings in the use of variable-speed pumping because the average head loss through the filter cake for a filter run is considerably less than the terminal head loss. This potential economy was not considered in this study and is an area of study for future modification of POPO. Some of the more recently constructed diatomite filtration plants utilize variable-speed pumping.

Backwashing Cost

The length of a filtering cycle is equal to the sum of the length of the filter run and the time needed for backwashing and precoating the filter for the next filter run. Water is not produced by the filter during the time needed for backwashing and precoating (down-time). To filter the same quantity of water, a filter has to operate at a slightly higher rate during the actual filtering period of the filter cycle than it would if filtering actually took place during the entire filter cycle. In addition, filtered water must be used for backwashing and the water run to waste during backwashing will have to be replaced by a slight increase in the flow rate.

It is assumed that the increase in costs resulting from providing filtered water for backwashing increases the operating costs proportionately -- i.e., the monthly cost of backwash water is equal to the total monthly operating cost times the ratio of the quantity of backwash water needed per month divided by the quantity of finished water produced per month. The need to provide backwash water would not increase the first cost of the plant unless it were so large a percentage of total production that additional filter area had to be provided.

The cost of producing the water that would have been produced during the down-time is computed as the operating costs (excluding power costs) times the ratio of down-time to length of filter run. Power costs are excluded from this computation because the total design flow is used to compute power costs.

The method used for calculating backwash costs is only approximate, but it eliminates the need for an iterative calculation process. The increase in the filtration rate that would be needed to overcome production loss during down-time and to provide backwash water will decrease the filter run length, and thus, increase the amount of down-time per day above that which is calculated based on the design filtration rate. The resulting increase in down-time is greater than the proportional increase in filtration rate (Equation 2 or 4). Thus, the filtration rate would have to be increased again to compensate for the more than proportional increase in down-time. Therefore, it is apparent that an iterative process would have to be used to find the actual combination of filtration rate and filter area that would result in the desired quantity of finished water being produced.

However, the method used in the POPO program for calculating backwashing costs should give good results because the backwashing cost is ordinarily a very small portion of the total operating cost. Backwashing cost cannot be neglected altogether because it can be a significant cost factor for very short filter runs. The method proposed would not be adequate for extremely short filter runs (less than four hours), but this inadequacy will not affect the use of the program since such extremely short runs do not provide optimum economy anyway.

An input data sheet prepared by a designer in making use of POPO is shown in Fig. 4 for one of the typical jobs discussed in the next section. Most of the data included are self-explanatory and illustrates the type of data the designer must provide in order to use POPO. Some items that may not be self-explanatory include:

Fig. 4. POPO Input Data.

```
P O P O -- PROGRAM FOR OPTIMIZATION OF PLANT OPERATION

       JOB 1.  IRON REMOVAL

  1 DESIGN FLOW               1      MGD
  2 SALVAGE VALUE            15      PERCENT FIRST COST
  3 ENERGY CONVERSION        70      PERCENT
  4 INTEREST RATE             4      PERCENT
  5 PLANT LIFE               25      YEARS
  6 SOLIDS  (CS)             7.5     PPM
  7 XI INDEX              1.95E9     FT/LB
  8 TEMPERATURE               55     DEGREES F
  9 PRECOAT WEIGHT          0.15     LB/SF
 10 PRECOAT DENSITY           15     LB/CF
 11 SEPTUM DIAMETER         FLAT     INCHES
 12 BETA PREDICTION     9.33/1.95/0/0
 13 UNIT FLOW RATE      0.4/0.2/1.8            GSFM
 14 BODY FEED           30/10/100              PPM
 15 TERMINAL HEAD       50/10/150              FT
 16 DIATOMITE COST          :00     $/TON
 17 FIRST COST          AREA        $/SF
                         100         225
                         200         160
                         350         128
                         600         110
                        1000         100
                        2000          94
  *                    25000          85
 18 POWER COST                2     CENTS/KWH
 19 LABOR COST          AREA        $/SF PER MONTH
                         100         2.00
                         200         1.15
                         300         0.83
                         500         0.63
                         800         0.50
                        2000         0.37
                        4500         0.30
                       13000         0.25
  *                    25000         0.24
 20 BACKWASH COST         10, 30    GAL/SF, MIN
   BEGIN
```

7. XI INDEX. This is the precoat resistance index (ξ). 1.95 E9 means 1.95×10^9.

12. BETA PREDICTION. This is the filter cake resistance prediction equation. The exponents b_1, b_2, b_3, b_4 of Equation 6 are input.

13. UNIT FLOW RATE. The various filtration rates analyzed in this job are from 0.4 to 1.8 gsfm in increments of 0.2 gsfm.

14. BODY FEED. The various body feed concentrations analyzed in this job are from 10 ppm to 30 ppm in increments of 2 ppm.

15. TERMINAL HEAD. The various terminal heads analyzed in this job are from 50 to 150 ft in increments of 10 ft.

17 and 19. The cost data obtained from curves of the type shown in Fig. 2 and Fig. 3 are input by tabulating a number of points along the cost-area curve.

20. BACKWASH COST. The total amount of backwash water (gal/sq ft), and the total down-time for each backwash (min) are input.

A more complete discussion of the details of the use of POPO is presented in a POPO User Manual (1,2).

The output calculated by POPO for Job No. 1 is illustrated in Fig. 5. POPO calculates the cost of all combinations required in the input data and outputs the 10 least cost combinations. Since the β-prediction equation may be somewhat high or low, the calculation is made for β values above and below the value obtained from the β-prediction equation. For each job, POPO optimizes the design for six β values from 50 to 175 percent of the value obtained from the input β-prediction equation. This is shown in Fig. 5 in the 6 groups of data, each group representing the 10 least cost alternatives for the level of β index indicated at the top of the group.

Fig. 5. POPO Output Data, Job 1.

```
FLOW  TERM   CD  B E T A  TIME  THICK * ----- COSTS, $ PER MILLION GALLONS ------ *  TOTAL
      HEAD         4  -2                *                   LAB+                   *   COST
GSFM   FT   PPM  10 FT     HR      IN   * TOTAL   1ST  OPER  MAIN  POWR  DIAT  BAKW *   $/MO
----------------------------------------*------------------------------------------*--------

                                 BETA INDEXES =  50 PERCENT OF PREDICTED VALUES
0.80   150   30    7160   15.0   0.26 *  65.9  14.2  51.7  13.3  13.5  22.9   2.0 *    2002
0.80   140   30    7160   14.0   0.25 *  65.9  14.2  51.7  13.3  12.6  23.7   2.2 *    2003
0.80   130   30    7160   13.0   0.24 *  66.1  14.2  51.9  13.3  11.7  24.5   2.4 *    2008
0.80   120   30    7160   12.0   0.24 *  66.4  14.2  52.3  13.3  10.8  25.5   2.6 *    2019
1.00   150   30    7160    9.6   0.24 *  66.6  12.3  54.3  12.3  13.5  25.5   3.1 *    2024
0.80   130   40    4086   17.1   0.34 *  66.8  14.2  52.7  13.3  11.7  25.8   1.8 *    2031
0.80   120   40    4086   15.8   0.32 *  66.9  14.2  52.7  13.3  10.8  26.6   2.0 *    2033
0.80   140   40    4086   18.4   0.36 *  66.9  14.2  52.7  13.3  12.6  25.1   1.7 *    2034
1.00   140   30    7160    9.0   0.23 *  66.9  12.3  54.6  12.3  12.6  26.4   3.3 *    2034
1.00   150   40    4086   12.6   0.32 *  66.9  12.3  54.6  12.3  13.5  26.6   2.3 *    2035

                                 BETA INDEXES =  75 PERCENT OF PREDICTED VALUES
0.80   150   40    6129   13.2   0.29 *  72.1  14.2  58.0  13.3  13.5  28.5   2.6 *    2192
0.80   140   40    6129   12.3   0.28 *  72.3  14.2  58.1  13.3  12.6  29.4   2.8 *    2198
0.80   150   30   10740   10.0   0.22 *  72.5  14.2  58.4  13.3  13.5  28.1   3.4 *    2205
0.60   150   30   10740   17.8   0.25 *  72.6  17.4  55.2  15.5  13.5  24.2   2.0 *    2207
0.80   130   40    6129   11.4   0.27 *  72.7  14.2  58.5  13.3  11.7  30.4   3.1 *    2209
0.60   140   30   10740   16.6   0.24 *  72.7  17.4  55.3  15.5  12.6  25.0   2.2 *    2211
0.60   130   30   10740   15.4   0.23 *  73.0  17.4  55.6  15.5  11.7  26.0   2.4 *    2219
0.80   140   30   10740    9.3   0.21 *  73.1  14.2  58.9  13.3  12.6  29.2   3.8 *    2222
0.80   120   40    6129   10.5   0.25 *  73.3  14.2  59.1  13.3  10.8  31.5   3.5 *    2227
0.60   130   40    6129   20.3   0.31 *  73.4  17.4  56.0  15.5  11.7  26.9   1.9 *    2231

                                 BETA INDEXES = 100 PERCENT OF PREDICTED VALUES
0.60   150   40    8172   17.5   0.29 *  77.2  17.4  59.8  15.5  13.5  28.5   2.3 *    2346
0.80   150   40    8172    9.9   0.25 *  77.3  14.2  63.2  13.3  13.5  32.5   3.8 *    2350
0.60   140   40    8172   16.4   0.28 *  77.3  17.4  59.9  15.5  12.6  29.4   2.5 *    2351
0.60   150   30   14321   13.3   0.22 *  77.5  17.4  60.1  15.5  13.5  28.1   3.0 *    2355
0.60   130   40    8172   15.2   0.27 *  77.7  17.4  60.2  15.5  11.7  30.4   2.7 *    2360
0.80   150   50    5289   12.2   0.32 *  77.8  14.2  63.6  13.3  13.5  33.6   3.1 *    2364
0.80   140   40    8172    9.2   0.24 *  77.9  14.2  63.8  13.3  12.6  33.6   4.2 *    2369
0.60   140   30   14321   12.5   0.21 *  78.0  17.4  60.6  15.5  12.6  29.2   3.3 *    2370
0.80   140   50    5289   11.4   0.30 *  78.1  14.2  63.9  13.3  12.6  34.6   3.4 *    2373
0.60   120   40    8172   14.0   0.25 *  78.2  17.4  60.8  15.5  10.8  31.5   3.0 *    2376

                                 BETA INDEXES = 125 PERCENT OF PREDICTED VALUES
0.60   150   40   10215   14.0   0.25 *  80.9  17.4  63.5  15.5  13.5  31.5   3.0 *    2460
0.60   140   40   10215   13.1   0.25 *  81.4  17.4  64.0  15.5  12.6  32.6   3.3 *    2473
0.60   150   50    6611   17.3   0.33 *  81.7  17.4  64.3  15.5  13.5  32.8   2.5 *    2484
0.60   140   50    6611   16.2   0.31 *  81.9  17.4  64.5  15.5  12.6  33.7   2.7 *    2489
0.60   130   40   10215   12.2   0.24 *  82.0  17.4  64.6  15.5  11.7  33.8   3.6 *    2493
0.80   150   50    6611    9.8   0.28 *  82.1  14.2  67.9  13.3  13.5  36.8   4.2 *    2494
0.60   130   50    6611   15.0   0.30 *  82.2  17.4  64.8  15.5  11.7  34.7   3.0 *    2500
0.60   150   30   17901   10.7   0.20 *  82.5  17.4  65.1  15.5  13.5  32.0   4.1 *    2507
0.80   140   50    6611    9.1   0.27 *  82.7  14.2  68.5  13.3  12.6  38.0   4.6 *    2514
0.80   150   40   10215    7.9   0.22 *  82.7  14.2  68.5  13.3  13.5  36.5   5.3 *    2514

                                 BETA INDEXES = 150 PERCENT OF PREDICTED VALUES
0.60   150   40   12258   11.7   0.23 *  84.8  17.4  67.3  15.5  13.5  34.5   3.9 *    2576
0.60   150   50    7933   14.5   0.29 *  84.8  17.4  67.4  15.5  13.5  35.2   3.2 *    2577
0.60   140   50    7933   13.5   0.28 *  85.2  17.4  67.8  15.5  12.6  36.3   3.4 *    2589
0.60   140   40   12258   10.9   0.22 *  85.5  17.4  68.1  15.5  12.6  35.7   4.3 *    2599
0.60   130   50    7933   12.5   0.27 *  85.8  17.4  68.4  15.5  11.7  37.5   3.8 *    2609
0.60   150   60    5559   17.2   0.37 *  86.2  17.4  68.8  15.5  13.5  37.1   2.7 *    2621
0.60   140   60    5559   16.0   0.35 *  86.4  17.4  69.0  15.5  12.6  38.0   2.9 *    2627
0.80   150   50    7933    8.1   0.25 *  86.5  14.2  72.3  13.3  13.5  40.0   5.4 *    2628
0.60   130   40   12258   10.1   0.22 *  86.5  17.4  69.1  15.5  11.7  37.2   4.7 *    2630
0.60   120   50    7933   11.6   0.26 *  86.7  17.4  69.3  15.5  10.8  38.8   4.2 *    2636

                                 BETA INDEXES = 175 PERCENT OF PREDICTED VALUES
0.60   150   50    9255   12.4   0.27 *  87.9  17.4  70.5  15.5  13.5  37.6   3.9 *    2672
0.60   140   50    9255   11.6   0.26 *  88.6  17.4  71.2  15.5  12.6  38.8   4.2 *    2692
0.60   150   40   14301   10.0   0.22 *  88.7  17.4  71.3  15.5  13.5  37.4   4.8 *    2695
0.60   150   60    6486   14.7   0.33 *  88.8  17.4  71.4  15.5  13.5  39.1   3.3 *    2700
0.60   140   60    6486   13.7   0.32 *  89.2  17.4  71.8  15.5  12.6  40.1   3.6 *    2712
0.60   130   50    9255   10.7   0.25 *  89.5  17.4  72.1  15.5  11.7  40.2   4.7 *    2720
0.60   140   40   14301    9.4   0.21 *  89.7  17.4  72.3  15.5  12.6  38.9   5.3 *    2728
0.60   130   60    6486   12.8   0.30 *  89.9  17.4  72.4  15.5  11.7  41.3   3.9 *    2731
0.40   150   40   14301   22.6   0.26 *  89.9  24.1  65.8  19.5  13.5  30.5   2.4 *    2733
0.40   140   40   14301   21.1   0.25 *  90.2  24.1  66.1  19.5  12.6  31.5   2.6 *    2742
```

Table 3. Summary of 13 Jobs Processed by POPO

Job	Q	Solids		Filter	Temp	Septum	t_r	β	((q, C_p, H))	$/MG		
	MGD	ppm	type	aid	^{o}F	inch	hr	10^4 ft^{-2}	For 100% β	Total	First	Oper
1	1	7.5	iron	C-503	55	Flat	17.5	8172	((0.6,40,150))	77.2	17.4	59.8
							9.9	8172	((0.8,40,150))	77.3	14.2	63.2
2	1	7.5	iron	C-503	55	1	18.1	8172	((0.8,40,140))	67.1	14.2	52.9
							19.7	8172	((0.8,40,150))	67.1	14.2	52.9
3	7	7.5	iron	C-503	55	3.5	14.4	6961	((0.8,40,150))	59.8	12.4	47.4
							10.8	11920	((0.8,30,150))	59.9	12.4	47.5
4	7	7.5	iron	HSC	55	3.5	9.9	9852	((0.8,40,150))	59.1	12.4	46.7
							12.4	6491	((0.8,50,150))	59.3	12.4	46.9
5	7	4	iron	HSC	55	3.5	13.7	7323	((1,25,150))	44.2	10.4	33.8
							12.7	7323	((1,25,140))	44.2	10.4	33.8
6	3	50*	KBC	HSC	48	1	11.2	5819	((1,50,150))	58.0	14.7	43.2
							9.8	5819	((1,50,135))	58.2	14.7	43.4
7	3	50*	KBC	HSC	72	1	11.6	9537	((1,40,150))	54.1	14.7	39.4
							10.2	9537	((1,40,135))	54.2	14.7	39.5
8	3	30*	WB	hSC	72	1	8.8	11725	((0.5,200,150))	140.6	25.8	114.8
							10.0	10308	((0.5,210,150))	140.7	25.8	114.9
9	4.5	8.5*	LSA	C-503	65	Flat	31.8	973	((0.73,24,25))	32.3	12.4	19.9
							26.0	1295	((0.73,22,25))	32.3	12.4	19.9
10	4.5	8.5*	LSA	HSC	65	Flat	16.5	1866	((0.73,24,25))	31.7	12.4	19.3
							14.9	2252	((0.73,22,25))	31.8	12.4	19.4
11	7	8.5*	LSA	HSC	65	Flat	6.0	824	((1.50,35,25))	27.6	7.1	20.5
							7.2	1151	((1.25,30,25))	27.7	8.1	19.6
12	7	8.5*	LSA	HSC	65	1	8.7	1708	((2.50,25,85))	21.3	5.2	16.2
							9.5	1708	((2.25,25,75))	21.4	5.5	15.9
13	25	8.5*	LSA	HSC	65	1	8.7	1708	((2.50,25,85))	19.9	4.9	15.0
							9.5	1708	((2.25,25,75))	19.9	5.2	14.7

HSC = Hyflo Super-Cel
KBC = Kentucky ball clay (Kaolinite)
WB = Wyoming bentonite (Montmorillonite)
LSA = Carry-over from lime-soda ash process

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* Turbidity units rather than ppm by weight

OPTIMUM DESIGN AND OPERATION

A summary of the results from 13 jobs processed by POPO is shown in Table 3. Data included for each job are: design flow for the plant (Q); type and concentration (C_S) of solids; grade of filter aid being considered; water temperature; type of septum; length of filter run (t_r); predicted β index; two most economical combinations ((q, C_D, H)) for 100 percent of predicted β values; and total, first, and operating costs (\$/MG).

Jobs 1-8, and Job 13 are presented to demonstrate the use of POPO for hypothetical installations. Jobs 9-12 are based on the determination of optimum operating conditions in a vacuum filtration plant at Lompoc, California (6).

In all 13 jobs, the cost-area curves shown in Figs. 2 and 3 were used to compute first cost and combined labor and maintenance costs. It should be kept in mind that actual costs for a particular installation could vary considerably from these two curves. In the runs for the Lompoc jobs, the same cost-area curves were used for both flat and cylindrical septa and for Job 12 in which pressure filters were assumed. Costs for these filter design variations would not, in practice, be the same. Still, some very interesting observations can be made from the POPO results for these 13 jobs. An appropriate β index prediction equation was used for each job (Table 2).

The first five jobs illustrate the filtration of an iron-bearing water of good filtrability typical of iron-bearing waters found in

Iowa.

Job 1 and 2 show the relative economy of 1 inch septa compared to flat septa, other conditions being the same. While the same first cost-area curves were used for both jobs, it is apparent that even if a significantly higher first cost-area curve were used for the 1 inch septa filters, they would still probably be more economical.

Jobs 3 and 4 show that the use of different grades of diatomite made little difference in the cost of filtration of this iron-bearing water.

Jobs 4 and 5 illustrate the relative cost when the iron content is changed from 7.5 ppm to 4 ppm. It is evident that filtration cost is not a linear function of iron content.

Jobs 6 and 7 illustrate the effect of temperature on the optimum design for filtration of University tap water with added kaolinite clay. At the higher temperature, optimum body feed concentration is lower and costs are therefore slightly lower. This water with kaolinite added had a high filtrability compared with the same water with added montmorillonite clay as illustrated by Jobs 7 and 8. The kaolinite-bearing water is much less costly to filter, even when the turbidity was nearly twice as high (50 units vs 30 units turbidity in unfiltered water).

The Lompoc runs (Jobs 9 and 10) illustrate the use of POPO to suggest optimum operating criteria under conditions in which the filter plant was already built. Vacuum filters with flat septa were provided in the Lompoc plant. Since filtration rate and terminal head were fixed by the plant construction, only the type and concentration of body feed could be changed and were changed in the POPO runs.

With the most helpful cooperation of water plant officials at Lompoc, the senior author spent nearly all of June, 1964 in collecting field data at Lompoc. Normal plant operating data were collected and special runs were made to collect data for development of β-prediction equations using different body feed concentrations.

The variables used in Job 9 approximate the conditions at the plant in the latter part of June, 1964. The cost-area curve shown in Fig. 2 was used for computing first cost and may not be entirely representative of the Lompoc plant. The actual first cost of the filtration portion of the Lompoc plant is somewhat less than the first cost determined from the curve shown in Fig. 2. The plant had been operating using C-503 filter aid in concentrations of about 20-25 ppm. The question was raised as to whether a finer filter aid might be more economical than C-503 filter aid for routine use. Jobs 9 and 10 were designed to answer this question.

Hyflo Super-Cel is a considerably finer filter aid than C-503. The ξ index is about $5(10)^9$ ft/lb for Hyflo Super-Cel and about $2(10)^9$ ft/lb for C-503. However, the differences in their β indices are less than corresponding differences in the ξ indices (2,3), and Hyflo Super-Cel costs significantly less than C-503. POPO was used to determine whether difference in prices of the two filter aids was great enough to make the use of the lower cost Hyflo Super-Cel economical, even though the resulting higher cake resistances will decrease the length of filter run and increase backwashing cost and the amount of precoat diatomite needed. If the costs are comparable between the two filter aids, it would probably be more desirable to use Hyflo Super-Cel because the finer filter aid can remove smaller particles.

Hyflo Super-Cel costs about $20/ton less than C-503. Comparison of the output from Jobs 9 and 10 (and also Jobs 3 and 4) illustrate, at least for these two particular cases, that the use of Hyflo Super-Cel under such a cost per ton differential will result in slightly lower total filtration costs.

The turbidity load to the Lompoc filters during June, 1964 ranged from about 3 to 11 units and was usually about 6 to 10 units. The optimum body feed for both C-503 and Hyflo Super-Cel under the specified conditions (Jobs 9 and 10) is 24 ppm for the lowest operating cost and 22 ppm for the second cheapest. The plant was actually being operated with 20 ppm body feed most of the time that data were being collected in Lompoc for this study, and therefore, the plant was being operated at very near the optimum body feed rate. In both Jobs 9 and 10, for β indices less than 100 percent of the predicted values and for $C_S = 8.5$ units, the optimum body feed concentrations were nearer to 20 ppm (1,2). Smaller β indices would be expected if the turbidity load to the filters were less than 8.5 units. Thus, the Lompoc plant was being operated at approximately the optimum body feed concentration.

In Job 11, it was assumed that the Lompoc plant was not yet constructed and POPO was used to design similar filter units for the plant at the ultimate design flow rate of 7 MGD. POPO was used to optimize filtration rate and body feed concentration for 25 ft terminal head loss, limited by the choice of vacuum filters. The results for Job 11 indicate that water could have been filtered more cheaply if the Lompoc plant had been designed to operate at a higher filtration rate and using higher body feed concentrations. (POPO was NOT available when the Lompoc plant was designed.)

Provision was made in the design of the Lompoc plant for the addition of new filter units to double the filter area for future expansion (6). According to the results of Job 11, it should be found that the present filter area is adequate for much larger plant flows and additional filter units may be unnecessary. However, it may be necessary to increase the capacity of some of the pumps, pipes and other equipment to handle the larger flows.

The specifications for the Lompoc plant indicated that the "length of filter run shall not be less than 14 hr for a plant flow of 7 MGD" (6). The length of filter run for many of the optimum combinations of Job 10 (using other than 100 percent of the predicted β index) is less than 14 hr, and the length of filter run for all of the optimum combinations in Job 11 is less than 14 hr. Thus, this specification was probably unwarranted unless there are reasons other than economy that the length of filter run should be at least 14 hr.

A further advantage of the use of shorter filter runs at Lompoc is in backwashing. The filters are more easily washed when the filter cakes are thinner. One of the difficulties observed in the operation of the Lompoc plant is that thick filter cakes are difficult to wash from the filter housings. In some cases, a filter had to be washed manually in order to remove the filter cake completely.

Job 12 results indicate that if pressure filters containing 1 inch septa were used at Lompoc that the optimum filtration rate would be even higher and overall economy might even be greater. The greater economy in Job 12, of course, is based partly on the erroneous assumption that the first cost and labor and maintenance cost are comparable for vacuum filters with flat septa and pressure filters with 1 inch septa since the same cost-area curves (Fig. 2 and 3) were used in Jobs 11 and 12.

Comparison of results from Jobs 12 and 13 illustrates that the total cost of filtering water per MG is less for plants of greater capacity. The reason for this is that first cost and labor and maintenance costs per MG are not constant but decrease with increasing capacity.

The results of the 13 jobs illustrate that the optimum design criteria combination ((q, C_D, H)) varies for each type of installation depending primarily on the filtrability of the water as represented by the β index prediction equation. As the filtrability decreases (higher β index), the optimum flow rate decreases and the body feed concentration and terminal head loss increase. In general, when total operating cost is high (low filtrability) compared with the first cost, the lower flow rates are more economical because first cost is a relatively small portion of the total cost and decreasing the flow rate decreases total operating cost.

The POPO results illustrate that the optimum design criteria for ((q, C_D, H)) depends on the particular situation and can vary considerably. The optimum flow rates ranged from 0.5 to 2.5 gsfm. Thus, the use of ANY PARTICULAR FIXED FILTRATION RATE for all plants SHOULD BE AVOIDED. Most of the present application of diatomite filters in the water supply field is in the filtration of water of relatively high filtrability. Thus, relatively higher optimum filtration rates are indicated. The water filtered at Massena, New York (7) is a water of very high filtrability.

According to information obtained from the Department of Public Works in Massena, the plant is presently (in 1965) filtering at about 0.5 gsfm and filter runs are 4 and 5 days long. In light of the POPO results, the Massena plant probably should have been designed to operate at 2 or 3 gsfm for greater economy.

The tremendous potential of POPO in both the design of new filtration plants and the optimization of existing plants is demonstrated in the above discussion. POPO can and should be used to optimize the operation of existing plants because total plant flow generally increases with time, and optimum operating conditions will change over the life of the plant.

SUMMARY AND CONCLUSIONS

The total cost of filtering potable water is a very complex function of several variables. Because of the complexity, reasonably accurate calculations of costs for varying conditions of operation have not been generally possible. As a result, filtration plants have traditionally been designed to be adequate, rather than to produce potable water at minimum cost. However, in the case of diatomite filtration, the desirable goal of practical least cost design is near reality. The problem is more difficult in the case of sand filtration because a generally acceptable mathematical expression for the head loss-time relationship of sand filters is not yet available.

The objective of this study was the development of and demonstration of the use of a digital computer program that could be used in the design of diatomite filtration plants for operation with optimum economy. In order to accomplish this, it was necessary to be able to predict the variation of filter cake resistance for various conditions since cake resistance is one of the primary factors influencing costs.

Diatomite filtration equations that were theoretically developed from the generally accepted filtration rate equation (2,3) were used to describe the head loss-time relationships during formation of diatomite filter cakes.

Empirical β-prediction equations (2,4) were used to describe the variation of filter cake resistance with body feed concentration, suspended solids concentration, and filter aid grade (where applicable).

The computer program developed in this study, called POPO (Program for Optimization of Plant Operation), is explained in detail elsewhere (1,2) in the form of a reference manual. Included in the user manual is an explanation of the use of POPO, a FORTRAN list of the actual program, and actual POPO output (similar to Fig. 5) for some hypothetical installations and for the Lompoc, California installation. A summary of the POPO output included in the reference manual is presented herein.

The following conclusions were drawn from the results of the POPO output for the 13 jobs included in this paper:

1. POPO has tremendous potential application in both the design of new diatomite filtration plants and in the optimization of the operation of existing diatomite filtration plants.

2. The combination of flow rate, body feed concentration, and terminal head loss, ((q, C_D, H)), that result in least cost depends entirely on the particular situation and can vary considerably. Therefore, the use of any particular design filtration rate for all types

of installations should be avoided and the optimum rate should be determined for each particular case.

3. The optimum combination ((q, C_D, H)) and the cost of filtration depend primarily on the filtrability of the water. Filtrability, as defined herein, refers only to head loss considerations as defined by the β-prediction equations. Effluent quality is assumed acceptable in all cases.

4. Results of the POPO output which are based on the type of solids filtered, the cost assumptions made, and the methods of cost computation used in POPO, indicated that:

   a. Cylindrical septa are theoretically more economical than flat septa; and the smaller the diameter of cylindrical septa, within practical limits, the greater the economy.

   b. Hyflo Super-Cel is probably more economical than C-503, even though its ξ index is considerably larger than the ξ index for C-503 because it costs less, and variations in ξ index result in relatively smaller variations in the β index. However, the relative economy of different grades should be checked in each case.

   c. Optimum design of filtration plants for waters of high filtrability (low β index) will occur at high filtration rates, low body feed concentrations and low terminal head losses. As filtrability decreases (β increases) optimum design will gradually change to low filtration rates, high body feed rates and high terminal head losses.

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PART VI

USER MANUAL FOR PROGRAM FOR OPTIMIZATION OF PLANT OPERATION

J. H. Dillingham
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Progress Report

- USER MANUAL -

PROGRAM FOR OPTIMIZATION OF PLANT OPERATION

(POPO)

by

James H. Dillingham
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E. Robert Baumann

Project 549-S

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- USER MANUAL -

PROGRAM FOR OPTIMIZATION OF PLANT OPERATION

(POPO)

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January 1, 1966

USER MANUAL FOR
PROGRAM FOR OPTIMIZATION OF PLANT OPERATION

POPO (Program for Optimization of Plant Operation) has been developed for use with the IBM 7074 computer system at Iowa State University. It has been coded in FORTRAN and a FORTRAN list of the entire program is included in this manual. The FORTRAN list includes a generous supply of comment statements (statements that begin with C in column 1) for the purpose of explaining the program and its logic. It is suggested that the FORTRAN list be examined even by those who are not familiar with the FORTRAN computer language.

POPO has been designed to optimize diatomite filtration plant design and/or operation by determining the optimum combination of unit flow rate (q), body feed concentration (C_D), and terminal head loss (H) that will result in production of filtered water at minimum cost. The optimum design combination of q, C_D, and H will be indicated in double parentheses, ((q, C_D, H)) for the data inserted by the designer in the POPO data sheet. POPO will optimize the operation of a particular type of installation filtering a water of known quality (or filtrability) using a particular grade of filter aid. Comparison of different types of installations and different types of filter aids requires repeated use of POPO. POPO has been developed for such use, and any number of POPO jobs can be processed in one computer run.

POPO can be used to optimize operation of existing plants. When used for this purpose, the body feed concentration will be the main variable to optimize. For existing plants, the unit flow rate (q) is fixed by the total flow through the plant and the available filter area. The terminal head loss may also be fixed depending upon the pumping head available and the type of equipment used to control flow rate through the filters. If the terminal head loss is not fixed, then POPO can be used to determine the optimum combination of body feed concentration and terminal head loss to be used with the existing plant flow rate.

POPO has been designed to be modified easily for special applications. The computation of each of the factors of cost (first cost, filter aid, labor, maintenance, power, and backwashing) and the necessary data input for their computation has been separated into separate computer subroutines (see FORTRAN list). If it becomes desirable to change the method of computation of any of the cost factors, this can be accomplished by simply changing the subroutine where the particular cost is computed -- even if the new method of computation requires a different type of data and a different method of data input. The methods of cost computation included in the present program were chosen because they were most suitable to many different types of installation.

POPO input has been designed to be largely self-explanatory. POPO data sheets have been prepared for the user's convenience (Table 1). A POPO data sheet simplifies data card preparation because it is only necessary to write in the values of the specified variables for each separate job. Each data card image read by POPO is reproduced on the first page of output and serves as a convenient description of the particular job (Table 2). POPO output for 13 jobs is included in this reference manual

Table 1. POPO Data Sheet

POPO DATA

JOB NO.

BY

1		DESIGN FLOW		MGD	
2		SALVAGE VALUE		PERCENT FIRST COST	
3		ENERGY CONVERSION		PERCENT	
4		INTEREST RATE		PERCENT	
5		PLANT LIFE		YEARS	
6		SOLIDS (CS)		PPM	
7		XI INDEX		FT/LB	
8		TEMPERATURE		DEGREES F	
9		PRECOAT WEIGHT		LB/SF	
10		PRECOAT DENSITY		LB/CF	
11		SEPTUM DIAMETER		INCHES	
12		BETA PREDICTION			
13		UNIT FLOW RATE			GSFM
14		BODY FEED			PPM
15		TERMINAL HEAD			FT
16		DIATOMITE COST		$/TON	
17		FIRST COST	AREA	$/SF	
	*				
18		POWER COST		CENTS/KWH	
19		LABOR COST	AREA	$/SF PER MONTH	
	*				
20		BACKWASH COST		GAL/SF, MIN	
	BEGIN				

for demonstration purposes. The first page of output for each job illustrates the input data cards used and serve as examples of data input.

Each type of input data card has its own typical card number punched in columns 4 and 5 (Table 1) and a brief description of the type of information contained on the card. The card number is referred to as the card index number of card index. This number is used by POPO to determine the type of information contained on the card. There are 21 different card indices for POPO. The first 20 are indicated on the POPO data sheet. Card index 21 is reserved for input of maintenance cost information. It is not included on the POPO data sheet because maintenance cost is included with labor cost. When POPO is used to process more than one job in one computer run, it may not be necessary to read in all of the input information for each job. Only that information which changes from one job to the next has to be read in. For example, see jobs 2 and 3 in Table 2.

Comment cards may be included in the input data deck as desired for purposes of explanation or further description. These comment cards will be included in the first page of the output with the summary of the input data cards, but are ignored by POPO. Any input card that has no index number or has an index number that is not between 1 and 21, inclusively, is treated as a comment card. An example of a comment card can be seen on the first page of output for Job 3 in Table 2. The card that reads

(PREDICTION EQ FOR RUNS 5032-5056, 5150-5156)

is a comment card. Also, the card that reads

JOB 3. SAME AS JOB 2 EXCEPT FOR FOLLOWING and the blank card that follows it are comment cards. A blank card may be included in Job 3 to improve readability.

CAUTION -- A comment card should not begin with a number or have the letters B or S punched in column 6.

The BEGIN card instructs POPO that all necessary data have been read in and the optimization can begin. The B of BEGIN must be punched in column 6.

A STOP card (with the S of STOP punched in column 6) is optional. It instructs POPO that all jobs have been completed.

Each data card and the information it contains is best explained by considering an example. The input data for Job 1 are listed on the output for Job 1 (see POPO output for Job 1 in Table 2). These data will be used to explain the individual input cards by index number.

1. The design flow for Job 1 is 1 MGD.

2. The salvage value of the plant after 25 years (plant life) is assumed to be 15 percent of the first cost of the plant.

3. Overall efficiency of converting electrical energy to actual work is assumed to be 70 percent.

4. The annual interest rate is taken as 4 percent.

5. A plant life of 25 years is used.

6. The water to be filtered contains 7.5 ppm iron. (POPO records C_S as CS)

7. The filter aid being considered has a ξ index of $1.95\ (10)^9$ ft/#*(exponents of 10 are entered by preceeding the exponent with the letter E, 1.95E9 = $1.95\ (10)^9$). (POPO records ξ as XI)

---

* # means pounds.

8. The water temperature is 55° F.

9. The weight of precoat used will be 0.15 #/sf.

10. The in-place bulk density of the precoat (γ_p) is taken as 15 #/cf. The value of γ_p used to determine β indices and the resulting prediction equation should be used. A value of γ_p must be specified on this card even when using flat septa because it is used to determine filter cake thickness for both flat and cylindrical septa as well as the length of filter run for cylindrical septa.

11. Flat septa are used in Job 1. If cylindrical septa were used, the septum diameter in inches would be punched in the card (see Job 2, Table 2).

12. This card contains the exponents of the β prediction equation which is representative of the filter cake resistance when filtering the suspended solids of card 6. In this case, the prediction equation is

$$\beta = 10^{9.33} (C_S/C_D)^{1.95} C_D^{0} \xi^{0} = 10^{9.33} (C_S/C_D)^{1.95}.$$

13. This card contains respectively the beginning, increment, and final values of unit flow rate to be used by POPO in making cost comparisons. In this case, the card instructs POPO that costs are to be computed and compared for q = 0.4, 0.6, 0.8, ..., 1.8 gsfm. If only one value of q is to be considered, only that value is entered (Job 9, Table 2).

14. This card contains respectively the beginning, increment, and final values of body feed concentration to be used by POPO in making cost comparisons. In other words, POPO is instructed to compute and compare costs for body feed concentrations (C_D) of 30, 40, 50, ..., 100 ppm.

15. This card contains respectively the beginning, increment, and final values of terminal head loss to be used by POPO in making cost comparisons. In other words, POPO is instructed to compute and compare costs for terminal head losses of 50, 60, 70, ..., 150 ft.

16. Cost of diatomite filter aid delivered to plant is $100 per ton. (Cost in 1965 at Massena, New York plant was $102 per ton, at Lompoc, California, it was $69 per ton).

17. The first cost card is followed by cards that contain points taken from a first cost ($/sf) - Area (log scale) curve (Fig. 1) for the particular plant. Each point requires a separate card. The cards must be in the order of increasing area, and the last point card must have an asterisk (or some character other than a blank) entered in column 6. For all jobs included in the Output section of this reference manual, the First Cost-Area curve shown in Fig. 1 was used. From this curve (and the input cards of Job 1) first costs are $225/sf for a 100 sf plant, $160/sf for a 200 sf plant, etc.

18. Power costs for Job 1 are computed on the basis of a unit cost of 2¢/kwh.

19. Same form as first cost input (card index = 17). In the present form of POPO, the combined cost of labor and maintenance are entered with card index 19. The labor cost card is followed by cards that contain points taken from an appropriate Labor and maintenance cost-Area curve (Fig. 2). For the 13 Jobs included in the Output section of this reference manual, the Labor and maintenance cost-Area curve shown in Fig. 2 was used. From this curve (and the input cards of Job 1), labor and maintenance costs are: for a 100 sf plant, $2.00/sf

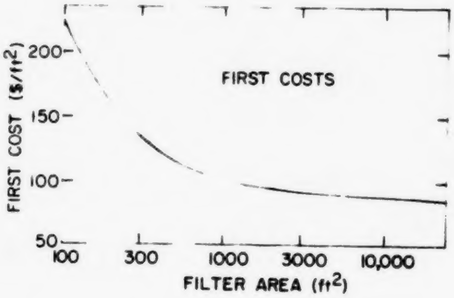

Fig. 1. Cost-Area curve for first cost

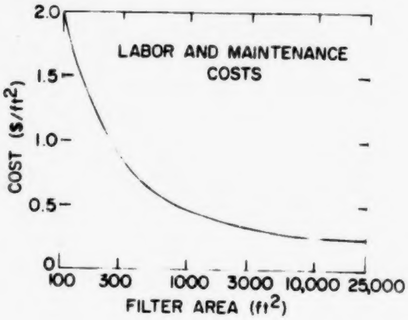

Fig. 2. Cost-Area curve for combined labor and maintenance costs

per month or $200 per month; for a 200 sf plant, $1.15/sf per month or $230 per month; etc. The cards must be in order of increasing area, and the last point card must have an asterisk (or some character other than a blank) entered in column 6.

20. The values contained on this card indicate that 10 gal of backwash water are wasted for each sf of filter area each time the filter is washed and the filter is out of operation for 30 minutes each time it is washed.

Use of POPO requires the preparation of the TWO COST CURVES (Figs. 1 and 2). Preferably, these curves should be prepared for each particular installation with a known design flow. For example, consider a plant with a design flow of 2 MGD (1 MGD is approximately 700 gpm). To prepare the cost curves, estimates of first cost and monthly labor and maintenance costs could be made for a plant of 1400 sf filtering at 1 gsfm, 2800 sf filtering at 0.5 gsfm, 700 sf filtering at 2 gsfm. The estimated costs are then divided by the filter area and plotted against the filter area (log scale). Smooth curves are then drawn through the points and these curves used to determine first cost and combined labor and maintenance cost for various filter areas (Figs. 1 and 2).

Points from the resulting curves are then used as input data for first cost (card index 17) and monthly labor and maintenance cost (card index 19). The points should be chosen from the curves in such a way that linear interpolation will not result in appreciable error.

If desirable, a log-log plot of cost per unit area versus area can be used for both first cost and labor and maintenance cost. A log-log plot would have less curvature and would probably be better when designing plants of 3 or 4 MGD or less.

When the cost curves are prepared in this way, the cost estimates are based on the total design flow or design capacity of the plant.

An alternative method of preparing the Cost-Area curves (Figs. 1 and 2) is to base the cost estimates on filtration rate rather than plant capacity. In this case, cost estimates for each filter area are made for the same filtration rate, say 1 gsfm.

The Cost-Area curves shown in Figs. 1 and 2 were determined from cost information that is representative, for the most part, of automated filtration plants filtering at 1 gsfm, and are therefore based on filtration rate rather than plant capacity. These curves were used for all 13 jobs of the POPO computer run included in this manual.

For cases where cost estimates are based on filtration rate, a rate factor has been introduced into POPO to compensate for different flow rates. The cost determined from the Cost-Area curves are multiplied by this rate factor. The rate factor is computed on the assumption that costs are 20 percent greater for each gsfm that the flow rate exceeds 1 gsfm -- e.g., rate factor = 1 at 1 gsfm, rate factor = 1.2 at 2 gsfm, rate factor = 1.4 at 3 gsfm, rate factor = 0.9 at 0.5 gsfm.

It is preferable for accuracy that cost estimates be based on plant capacity rather than filtration rate when designing diatomite filtration plants. This eliminates the need for the rate factor. However, it is more practical to base cost estimates on filtration rate because Cost-Area curves based on filtration rate can be more easily adjusted for use in the subsequent design of other filtration plants.

Two copies of POPO are available. The only difference in the two programs is in the two subroutines where first cost (CFUST, see FORTRAN list) and labor and maintenance cost (CLABR) are computed. In one copy these two subroutines do not include a rate factor (costs based on plant capacity), and in the other, the rate factor is included in these two subroutines (costs based on filtration rate).

The copy of POPO with the rate factor included was used for all 13 jobs included in the Output section.

Annotated POPO output is mostly self-explanatory. On the first page of output for each job (see Output section in Table 2) are the card images for input data cards for the particular job. The POPO results then follow. The printed results include the 10 most economical combinations ((q, C_D, H)) for β indices equal to 50, 75, 100, 125, 150, and 175 percent of those predicted by the β-prediction equation. Results for different percentages of β index are included because actual β indices may vary considerably from predicted values depending on the accuracy of the prediction equation.

Final choice of optimum ((q, C_D, H)) to be used in the plant design is left up to the designer. Values printed for each of the 10 least cost combinations include the flow rate (gsfm), terminal head loss (ft), body feed concentration (ppm), β index ($10^4 ft^{-2}$), length of filter run (hr), terminal cake thickness including precoat thickness (inch), and filtering costs including: total cost, first cost, operating cost, maintenance cost, power cost, diatomite cost, and backwash cost all expressed in dollars per million gallons ($/MG) as well as the total monthly cost ($/mo). (In the POPO output, (gsfm) is (GSFM) and β is BETA).

Table 2. POPO OUTPUT.

```
P O P O -- PROGRAM FOR OPTIMIZATION OF PLANT OPERATION

      JOB 1.  IRON REMOVAL

 1 DESIGN FLOW                 1      MGD
 2 SALVAGE VALUE              15      PERCENT FIRST COST
 3 ENERGY CONVERSION          70      PERCENT
 4 INTEREST RATE               4      PERCENT
 5 PLANT LIFE                 25      YEARS
 6 SOLIDS  (CS)              7.5      PPM
 7 XI INDEX               1.95E9      FT/LB
 8 TEMPERATURE                55      DEGREES F
 9 PRECOAT WEIGHT           0.15      LB/SF
10 PRECOAT DENSITY            15      LB/CF
11 SEPTUM DIAMETER          FLAT      INCHES
12 BETA PREDICTION       9.33/1.95/0/0
13 UNIT FLOW RATE    .   0.4/0.2/1.8            GSFM
14 BODY FEED             30/10/100              PPM
15 TERMINAL HEAD         50/10/150              FT
16 DIATOMITE COST            100      $/TON
17 FIRST COST             AREA        $/SF
                           100         225
                           200         160
                           350         128
                           500         110
                          1000         100
                          2000          94
 *                       25000          85
18 POWER COST                  2      CENTS/KWH
19 LABOR COST             AREA        $/SF PER MONTH
                           100         2.00
                           200         1.15
                           300         0.83
                           500         0.63
                           800         0.50
                          2000         0.37
                          4500         0.30
                         13000         0.25
 *                       25000         0.24
20 BACKWASH COST          10, 30      GAL/SF, MIN
  BEGIN
```

```
                                               JOB 1

FLOW  TERM    CD  B E T A  TIME  THICK * ----- COSTS, $ PER MILLION GALLONS ------ *   TOTAL
      HEAD          4  -2                *                      LAB+                *    COST
GSFM   FT    PPM  10 FT      HR      IN  * TOTAL   1ST  OPER  MAIN  POWR  DIAT  BAKW *    $/MO
-----------------------------------------*------------------------------------------*--------

                                BETA INDEXES =  50 PERCENT OF PREDICTED VALUES
0.80   150    30     7160   15.0   0.26 *  65.9  14.2  51.7  13.3  13.5  22.9   2.0 *    2002
0.80   140    30     7160   14.0   0.25 *  65.9  14.2  51.7  13.3  12.6  23.7   2.2 *    2003
0.80   130    30     7160   13.0   0.24 *  66.1  14.2  51.9  13.3  11.7  24.5   2.4 *    2008
0.80   120    30     7160   12.0   0.24 *  66.4  14.2  52.3  13.3  10.8  25.5   2.6 *    2019
1.00   150    30     7160    9.6   0.24 *  66.6  12.3  54.3  12.3  13.5  25.5   3.1 *    2024
0.80   130    40     4086   17.1   0.34 *  66.8  14.2  52.7  13.3  11.7  25.8   1.8 *    2031
0.80   120    40     4086   15.8   0.32 *  66.9  14.2  52.7  13.3  10.8  26.6   2.0 *    2033
0.80   140    40     4086   18.4   0.36 *  66.9  14.2  52.7  13.3  12.6  25.1   1.7 *    2034
1.00   140    30     7160    9.0   0.23 *  66.9  12.3  54.6  12.3  12.6  26.4   3.3 *    2034
1.00   150    40     4086   12.6   0.32 *  66.9  12.3  54.6  12.3  13.5  26.6   2.3 *    2035

                                BETA INDEXES =  75 PERCENT OF PREDICTED VALUES
0.80   150    40     6129   13.2   0.29 *  72.1  14.2  58.0  13.3  13.5  28.5   2.6 *    2192
0.80   140    40     6129   12.3   0.28 *  72.3  14.2  58.1  13.3  12.6  29.4   2.8 *    2198
0.80   150    30    10740   10.0   0.22 *  72.5  14.2  58.4  13.3  13.5  28.1   3.4 *    2205
0.60   150    30    10740   17.8   0.25 *  72.6  17.4  55.2  15.5  13.5  24.2   2.0 *    2207
0.80   130    40     6129   11.4   0.27 *  72.7  14.2  58.5  13.3  11.7  30.4   3.1 *    2209
0.60   140    30    10740   16.6   0.24 *  72.7  17.4  55.3  15.5  12.6  25.0   2.2 *    2211
0.60   130    30    10740   15.4   0.23 *  73.0  17.4  55.6  15.5  11.7  26.0   2.4 *    2219
0.80   140    30    10740    9.3   0.21 *  73.1  14.2  58.9  13.3  12.6  29.2   3.8 *    2222
0.80   120    40     6129   10.5   0.25 *  73.3  14.2  59.1  13.3  10.8  31.5   3.5 *    2227
0.60   130    40     6129   20.3   0.31 *  73.4  17.4  56.0  15.5  11.7  26.9   1.9 *    2231

                                BETA INDEXES = 100 PERCENT OF PREDICTED VALUES
0.60   150    40     8172   17.5   0.29 *  77.2  17.4  59.8  15.5  13.5  28.5   2.3 *    2346
0.80   150    40     8172    9.9   0.25 *  77.3  14.2  63.2  13.3  13.5  32.5   3.8 *    2350
0.60   140    40     8172   16.4   0.28 *  77.3  17.4  59.9  15.5  12.6  29.4   2.5 *    2351
0.60   150    30    14321   13.3   0.22 *  77.5  17.4  60.1  15.5  13.5  28.1   3.0 *    2355
0.60   130    40     8172   15.2   0.27 *  77.7  17.4  60.2  15.5  11.7  30.4   2.7 *    2360
0.80   150    50     5289   12.2   0.32 *  77.8  14.2  63.6  13.3  13.5  33.6   3.1 *    2364
0.80   140    40     8172    9.2   0.24 *  77.9  14.2  63.8  13.3  12.6  33.6   4.2 *    2369
0.60   140    30    14321   12.5   0.21 *  78.0  17.4  60.6  15.5  12.6  29.2   3.3 *    2370
0.80   140    50     5289   11.4   0.30 *  78.1  14.2  63.9  13.3  12.6  34.6   3.4 *    2373
0.60   120    40     8172   14.0   0.25 *  78.2  17.4  60.8  15.5  10.8  31.5   3.0 *    2376

                                BETA INDEXES = 125 PERCENT OF PREDICTED VALUES
0.60   150    40    10215   14.0   0.25 *  80.9  17.4  63.5  15.5  13.5  31.5   3.0 *    2460
0.60   140    40    10215   13.1   0.25 *  81.4  17.4  64.0  15.5  12.6  32.6   3.3 *    2473
0.60   150    50     6611   17.3   0.33 *  81.7  17.4  64.3  15.5  13.5  32.8   2.5 *    2484
0.60   140    50     6611   16.2   0.31 *  81.9  17.4  64.5  15.5  12.6  33.7   2.7 *    2489
0.60   130    40    10215   12.2   0.24 *  82.0  17.4  64.6  15.5  11.7  33.8   3.6 *    2493
0.80   150    50     6611    9.8   0.28 *  82.1  14.2  67.9  13.3  13.5  36.8   4.2 *    2494
0.60   130    50     6611   15.0   0.30 *  82.2  17.4  64.8  15.5  11.7  34.7   3.0 *    2500
0.60   150    30    17901   10.7   0.20 *  82.5  17.4  65.1  15.5  13.5  32.0   4.1 *    2507
0.80   140    50     6611    9.1   0.27 *  82.7  14.2  68.5  13.3  12.6  38.0   4.6 *    2514
0.80   150    [illegible]    10215    7.9   0.22 *  82.7  14.2  68.5  13.3  13.5  36.5   5.3 *    2514

                                BETA INDEXES = 150 PERCENT OF PREDICTED VALUES
0.60   150    40    12258   11.7   0.23 *  84.8  17.4  67.3  15.5  13.5  34.5   3.9 *    2576
0.60   150    50     7933   14.5   0.29 *  84.8  17.4  67.4  15.5  13.5  35.2   3.2 *    2577
0.60   140    50     7933   13.5   0.28 *  85.2  17.4  67.8  15.5  12.6  36.3   3.4 *    2589
0.60   140    40    12258   10.9   0.22 *  85.5  17.4  68.1  15.5  12.6  35.7   4.3 *    2599
0.60   130    50     7933   12.5   0.27 *  85.8  17.4  68.4  15.5  11.7  37.5   3.8 *    2609
0.60   150    60     5559   17.2   0.37 *  86.2  17.4  68.8  15.5  13.5  37.1   2.7 *    2621
0.60   140    60     5559   16.0   0.35 *  86.4  17.4  69.0  15.5  12.6  38.0   2.9 *    2627
0.80   150    50     7933    8.1   0.25 *  86.5  14.2  72.3  13.3  13.5  40.0   5.4 *    2628
0.60   130    40    12258   10.1   0.22 *  86.5  17.4  69.1  15.5  11.7  37.2   4.7 *    2630
0.60   120    50     7933   11.6   0.26 *  86.7  17.4  69.3  15.5  10.8  38.8   4.2 *    2636

                                BETA INDEXES = 175 PERCENT OF PREDICTED VALUES
0.60   150    50     9255   12.4   0.27 *  87.9  17.4  70.5  15.5  13.5  37.6   3.9 *    2672
0.60   140    50     9255   11.6   0.26 *  88.6  17.4  71.2  15.5  12.6  38.8   4.2 *    2692
0.60   150    40    14301   10.0   0.22 *  88.7  17.4  71.3  15.5  13.5  37.4   4.8 *    2695
0.60   150    60     6486   14.7   0.33 *  88.8  17.4  71.4  15.5  13.5  39.1   3.3 *    2700
0.60   140    60     6486   13.7   0.32 *  89.2  17.4  71.8  15.5  12.6  40.1   3.6 *    2712
0.60   130    50     9255   10.7   0.25 *  89.5  17.4  72.1  15.5  11.7  40.2   4.7 *    2720
0.60   140    40    14301    9.4   0.21 *  89.7  17.4  72.3  15.5  12.6  38.9   5.3 *    2728
0.60   130    60     6486   12.8   0.30 *  89.9  17.4  72.4  15.5  11.7  41.3   3.9 *    2731
0.40   150    40    14301   22.6   0.26 *  89.9  24.1  65.8  19.5  13.5  30.5   2.4 *    2733
0.40   140    40    14301   21.1   0.25 *  90.2  24.1  66.1  19.5  12.6  31.5   2.6 *    2742
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                      JOB 2.  SAME AS JOB 1 EXCEPT FOR USE OF 1 INCH
                              DIAMETER SEPTA  (CYLINDRICAL)

              11 SEPTUM DIAMETER                    1  INCH
                BEGIN
          ______________________________________________________________

FLOW  TERM   CD  B E T A  TIME   THICK * ----- COSTS, $ PER MILLION GALLONS ------ *   TOTAL
      HEAD         4  -2                *                       LAB+                 *    COST
GSFM   FT   PPM  10 FT     HR      IN  * TOTAL   1ST  OPER  MAIN  POWR  DIAT  BAKW *    $/MO
---------------------------------------*------------------------------------------*--------

                         BETA INDEXES =  50 PERCENT OF PREDICTED VALUES
1.00  130   30    7160   15.7    0.26 *  58.3  12.3  45.9  12.3  11.7  20.4   1.6 *   1770
1.00  140   30    7160   17.2    0.27 *  58.3  12.3  46.0  12.3  12.6  19.5   1.4 *   1772
1.00  120   30    7160   14.3    0.25 *  58.4  12.3  46.0  12.3  10.8  21.2   1.8 *   1774
1.00  150   30    7160   18.8    0.28 *  58.5  12.3  46.2  12.3  13.5  19.2   1.3 *   1777
0.80  120   30    7160   23.5    0.28 *  58.6  14.2  44.4  13.3  10.8  19.2   1.1 *   1780
0.80  110   30    7160   21.1    0.27 *  58.6  14.2  44.4  13.3   9.9  19.9   1.3 *   1780
1.00  110   30    7160   12.9    0.23 *  58.7  12.3  46.3  12.3   9.9  22.2   2.0 *   1783
0.80  130   30    7160   25.9    0.30 *  58.7  14.2  44.5  13.3  11.7  18.5   1.0 *   1784
0.80  100   30    7160   18.7    0.25 *  58.8  14.2  44.6  13.3   9.0  20.8   1.4 *   1786
1.00  110   40    4086   19.4    0.33 *  58.9  12.3  46.6  12.3   9.9  23.1   1.3 *   1790

                         BETA INDEXES =  75 PERCENT OF PREDICTED VALUES
0.80  140   30   10740   17.3    0.24 *  63.3  14.2  49.1  13.3  12.6  21.5   1.6 *   1923
0.80  150   30   10740   18.8    0.25 *  63.3  14.2  49.1  13.3  13.5  20.8   1.5 *   1924
0.80  130   30   10740   15.8    0.23 *  63.4  14.2  49.2  13.3  11.7  22.4   1.8 *   1927
1.00  140   40    6129   15.7    0.30 *  63.5  12.3  51.2  12.3  12.6  24.6   1.8 *   1931
1.00  150   40    6129   17.1    0.31 *  63.6  12.3  51.3  12.3  13.5  24.0   1.6 *   1932
1.00  130   40    6129   14.3    0.28 *  63.6  12.3  51.3  12.3  11.7  25.4   2.0 *   1934
0.80  120   40    6129   21.4    0.31 *  63.6  14.2  49.5  13.3  10.8  24.0   1.4 *   1934
0.80  130   40    6129   23.8    0.33 *  63.6  14.2  49.5  13.3  11.7  23.2   1.2 *   1934
0.80  120   30   10740   14.4    0.22 *  63.7  14.2  49.5  13.3  10.8  23.3   2.1 *   1936
1.00  150   30   10740   11.5    0.22 *  63.8  12.3  51.4  12.3  13.5  23.3   2.4 *   1938

                         BETA INDEXES = 100 PERCENT OF PREDICTED VALUES
0.80  140   40    8172   18.1    0.28 *  67.1  14.2  52.9  13.3  12.6  25.3   1.7 *   2040
0.80  150   40    8172   19.7    0.30 *  67.1  14.2  52.9  13.3  13.5  24.6   1.6 *   2040
0.80  130   40    8172   16.5    0.27 *  67.3  14.2  53.1  13.3  11.7  26.1   1.9 *   2044
0.80  150   30   14321   13.4    0.22 *  67.5  14.2  53.3  13.3  13.5  24.2   2.3 *   2051
0.80  120   40    8172   14.9    0.26 *  67.6  14.2  53.4  13.3  10.8  27.1   2.2 *   2054
1.00  150   40    8172   12.0    0.26 *  67.7  12.3  55.3  12.3  13.5  27.1   2.5 *   2056
0.80  140   30   14321   12.4    0.21 *  67.8  14.2  53.6  13.3  12.6  25.1   2.6 *   2060
1.00  140   40    8172   11.0    0.25 *  68.0  12.3  55.6  12.3  12.6  28.0   2.8 *   2065
0.80  110   40    8172   13.5    0.25 *  68.1  14.2  54.0  13.3   9.9  28.3   2.5 *   2071
0.80  130   50    5289   23.2    0.37 *  68.1  14.2  54.0  13.3  11.7  27.6   1.4 *   2071

                         BETA INDEXES = 125 PERCENT OF PREDICTED VALUES
0.80  150   40   10215   15.0    0.26 *  70.3  14.2  56.1  13.3  13.5  27.1   2.2 *   2137
0.80  140   40   10215   13.8    0.25 *  70.6  14.2  56.4  13.3  12.6  28.0   2.4 *   2144
0.80  150   50    6611   20.8    0.35 *  70.9  14.2  56.7  13.3  13.5  28.3   1.6 *   2155
0.80  140   50    6611   19.0    0.33 *  70.9  14.2  56.7  13.3  12.6  29.0   1.8 *   2156
0.80  130   40   10215   12.6    0.24 *  71.0  14.2  56.8  13.3  11.7  29.1   2.7 *   2158
0.80  130   50    6611   17.2    0.31 *  71.1  14.2  56.9  13.3  11.7  29.9   2.0 *   2160
0.80  120   50    6611   15.6    0.30 *  71.4  14.2  57.2  13.3  10.8  30.9   2.3 *   2171
0.60  140   40   10215   26.2    0.30 *  71.5  17.4  54.1  15.5  12.6  24.6   1.4 *   2172
0.60  130   40   10215   23.8    0.28 *  71.5  17.4  54.1  15.5  11.7  25.4   1.5 *   2174
1.00  150   50    6611   12.4    0.30 *  71.5  12.3  59.2  12.3  13.5  30.9   2.6 *   2174

                         BETA INDEXES = 150 PERCENT OF PREDICTED VALUES
0.80  150   50    7933   16.4    0.30 *  73.5  14.2  59.3  13.3  13.5  30.4   2.1 *   2234
0.80  150   40   12258   12.0    0.23 *  73.6  14.2  59.4  13.3  13.5  29.7   2.9 *   2236
0.80  140   50    7933   15.0    0.29 *  73.7  14.2  59.5  13.3  12.6  31.2   2.4 *   2240
0.60  150   40   12258   22.7    0.28 *  73.9  17.4  56.5  15.5  13.5  25.8   1.6 *   2245
0.60  140   40   12258   20.8    0.26 *  74.0  17.4  56.5  15.5  12.6  26.7   1.8 *   2248
0.80  140   40   12258   11.1    0.23 *  74.1  14.2  59.9  13.3  12.6  30.8   3.3 *   2252
0.80  130   50    7933   13.7    0.28 *  74.1  14.2  59.9  13.3  11.7  32.2   2.7 *   2252
0.60  130   40   12258   19.0    0.25 *  74.2  17.4  56.8  15.5  11.7  27.6   2.0 *   2255
0.60  120   40   12258   17.3    0.24 *  74.7  17.4  57.2  15.5  10.8  28.7   2.3 *   2269
0.60  150   30   21481   15.6    0.20 *  74.7  17.4  57.3  15.5  13.5  25.9   2.4 *   2269

                         BETA INDEXES = 175 PERCENT OF PREDICTED VALUES
0.80  150   50    9255   13.5    0.27 *  76.1  14.2  62.0  13.3  13.5  32.4   2.7 *   2314
0.60  150   40   14301   18.8    0.25 *  76.2  17.4  58.8  15.5  13.5  27.7   2.1 *   2316
0.60  140   40   14301   17.3    0.24 *  76.5  17.4  59.1  15.5  12.6  28.7   2.3 *   2324
0.80  140   50    9255   12.4    0.26 *  76.6  14.2  62.4  13.3  12.6  33.4   3.0 *   2327
0.60  150   50    9255   26.0    0.33 *  76.7  17.4  59.3  15.5  13.5  28.8   1.5 *   2332
0.60  140   50    9255   23.8    0.32 *  76.8  17.4  59.3  15.5  12.6  29.6   1.7 *   2333
0.80  150   60    6486   17.8    0.35 *  76.9  14.2  62.7  13.3  13.5  33.8   2.1 *   2336
0.60  130   50    9255   21.6    0.30 *  76.9  17.4  59.5  15.5  11.7  30.5   1.9 *   2338
0.80  150   40   14301   10.0    0.22 *  76.9  14.2  62.8  13.3  13.5  32.2   3.7 *   2339
0.60  130   40   14301   15.9    0.23 *  76.9  17.4  59.5  15.5  11.7  29.8   2.5 *   2339
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                           JOB 3.  SAME AS JOB 2 EXCEPT FOR FOLLOWING

                       1 DESIGN FLOW                  7    MGD
                       7 XI INDEX                1.95E9    FT/LB  (CELITE 503)
                      11 SEPTUM DIAMETER            3.5    INCHES
                      12 BETA PREDICTION      6.09/1.87/0/0.335
                             (PREDICTION EQ FOR RUNS 5032-5056, 5150-5156)
                      18 POWER COST                 1.5    CENTS/KWH
                        BEGIN
                      _____________________________________________________

FLOW   TERM   CC   B E T A   TIME   THICK * ----- COSTS, $ PER MILLION GALLONS ------ *   TOTAL
       HEAD          4  -2                *                     LAB+                   *    COST
GSFM    FT    PPM  10 FT       HR      IN * TOTAL   1ST  OPER  MAIN  POWR  DIAT  BAKW *    $/MO
------------------------------------------*-------------------------------------------*--------

                                BETA INDEXES =  50 PERCENT OF PREDICTED VALUES
1.00   150    30    5960     14.3    0.27 *  50.1  10.4  39.6   6.8  10.1  21.3   1.5 *   10650
1.00   140    30    5960     13.2    0.26 *  50.2  10.4  39.8   6.8   9.4  21.9   1.6 *   10683
1.00   130    30    5960     12.2    0.25 *  50.5  10.4  40.1   6.8   8.8  22.7   1.8 *   10744
0.80   140    30    5960     21.1    0.30 *  50.6  12.4  38.2   7.8   9.4  19.9   1.1 *   10769
0.80   150    30    5960     22.8    0.31 *  50.7  12.4  38.2   7.8  10.1  19.4   1.0 *   10778
1.20   150    30    5960      9.8    0.25 *  50.7   9.1  41.5   6.1  10.1  23.2   2.2 *   10781
0.80   130    30    5960     19.5    0.29 *  50.7  12.4  38.3   7.8   8.8  20.5   1.2 *   10782
0.80   120    30    5960     17.8    0.27 *  50.9  12.4  38.4   7.8   8.1  21.3   1.3 *   10822
1.00   120    30    5960     11.2    0.24 *  51.0  10.4  40.5   6.8   8.1  23.6   2.0 *   10842
1.20   140    30    5960      9.1    0.24 *  51.0   9.1  41.9   6.1   9.4  24.0   2.4 *   10859

                                BETA INDEXES =  75 PERCENT OF PREDICTED VALUES
0.80   150    30    6940     14.7    0.25 *  55.2  12.4  42.8   7.8  10.1  23.1   1.7 *   11744
0.80   140    30    8940     13.6    0.24 *  55.5  12.4  43.1   7.8   9.4  24.0   1.9 *   11810
0.80   130    30    8940     12.6    0.23 *  56.0  12.4  43.6   7.8   8.8  24.9   2.1 *   11910
1.00   150    30    8940      9.3    0.22 *  56.0  10.4  45.6   6.8  10.1  26.0   2.7 *   11921
1.00   150    40    5220     12.4    0.30 *  56.1  10.4  45.7   6.8  10.1  26.8   2.1 *   11943
0.80   150    40    5220     19.8    0.34 *  56.2  12.4  43.8   7.8  10.1  24.6   1.3 *   11958
0.80   140    40    5220     18.3    0.33 *  56.3  12.4  43.9   7.8   9.4  25.2   1.4 *   11976
1.00   140    40    5220     11.5    0.28 *  56.5  10.4  46.0   6.8   9.4  27.6   2.3 *   12012
0.80   130    40    5220     16.9    0.31 *  56.5  12.4  44.1   7.8   8.8  25.9   1.6 *   12020
0.60   150    30    8940     26.7    0.29 *  56.6  15.7  40.9   9.5  10.1  20.3   1.0 *   12040

                                BETA INDEXES = 100 PERCENT OF PREDICTED VALUES
0.80   150    40    6961     14.4    0.29 *  59.8  12.4  47.4   7.8  10.1  27.5   2.0 *   12726
0.80   150    30   11920     10.8    0.21 *  59.9  12.4  47.5   7.8  10.1  26.9   2.6 *   12745
0.60   150    30   11920     19.6    0.25 *  59.9  15.7  44.2   9.5  10.1  23.1   1.5 *   12750
0.80   140    40    6961     13.4    0.27 *  60.2  12.4  47.8   7.8   9.4  28.3   2.2 *   12805
0.60   140    30   11920     18.2    0.24 *  60.2  15.7  44.5   9.5   9.4  24.0   1.6 *   12811
0.80   140    30   11920     10.1    0.21 *  60.6  12.4  48.2   7.8   9.4  28.0   2.9 *   12892
0.60   130    30   11920     16.8    0.23 *  60.6  15.7  45.0   9.5   8.8  24.9   1.8 *   12904
0.80   130    40    6961     12.3    0.26 *  60.7  12.4  48.3   7.8   8.8  29.3   2.4 *   12919
1.00   150    40    6961      9.1    0.25 *  60.9  10.4  50.5   6.8  10.1  30.5   3.1 *   12960
0.60   150    40    6961     26.4    0.34 *  61.0  15.7  45.3   9.5  10.1  24.6   1.1 *   12976

                                BETA INDEXES = 125 PERCENT OF PREDICTED VALUES
0.60   150    30   14901     15.4    0.22 *  63.3  15.7  47.6   9.5  10.1  26.0   2.1 *   13476
0.80   150    40    8701     11.3    0.25 *  63.5  12.4  51.1   7.8  10.1  30.5   2.7 *   13517
0.60   150    40    8701     20.6    0.30 *  63.6  15.7  47.9   9.5  10.1  26.8   1.6 *   13535
0.60   140    40    8701     19.1    0.28 *  63.9  15.7  48.2   9.5   9.4  27.6   1.7 *   13592
0.60   140    30   14901     14.4    0.21 *  63.9  15.7  48.2   9.5   9.4  27.0   2.3 *   13594
0.80   140    40    8701     10.5    0.24 *  64.2  12.4  51.8   7.8   9.4  31.5   3.0 *   13659
0.60   130    40    8701     17.6    0.27 *  64.3  15.7  48.6   9.5   8.8  28.5   1.9 *   13681
0.80   150    50    5732     14.3    0.32 *  64.3  12.4  51.9   7.8  10.1  31.8   2.2 *   13688
0.60   130    30   14901     13.3    0.21 *  64.6  15.7  49.0   9.5   8.8  28.2   2.5 *   13754
0.80   140    50    5732     13.2    0.31 *  64.7  12.4  52.3   7.8   9.4  32.6   2.4 *   13777

                                BETA INDEXES = 150 PERCENT OF PREDICTED VALUES
0.60   150    40   10441     16.9    0.27 *  66.3  15.7  50.6   9.5  10.1  29.0   2.0 *   14104
0.60   140    40   10441     15.7    0.26 *  66.8  15.7  51.1   9.5   9.4  29.9   2.2 *   14205
0.60   150    30   17881     12.8    0.20 *  66.8  15.7  51.1   9.5  10.1  28.8   2.7 *   14219
0.80   150    40   10441      9.3    0.23 *  67.3  12.4  54.9   7.8  10.1  33.4   3.6 *   14330
0.60   130    40   10441     14.5    0.25 *  67.4  15.7  51.7   9.5   8.8  31.0   2.5 *   14346
0.80   150    50    6879     11.7    0.29 *  67.4  12.4  55.0   7.8  10.1  34.2   2.9 *   14349
0.60   150    50    6879     21.4    0.35 *  67.5  15.7  51.8   9.5  10.1  30.6   1.6 *   14362
0.60   140    30   17881     11.9    0.20 *  67.7  15.7  52.0   9.5   9.4  30.0   3.0 *   14395
0.60   140    50    6879     19.8    0.33 *  67.8  15.7  52.1   9.5   9.4  31.3   1.8 *   14418
0.80   140    50    6879     10.8    0.28 *  68.1  12.4  55.7   7.8   9.4  35.2   3.2 *   14491

                                BETA INDEXES = 175 PERCENT OF PREDICTED VALUES
0.60   150    40   12181     14.3    0.24 *  69.0  15.7  53.3   9.5  10.1  31.2   2.5 *   14683
0.60   140    40   12181     13.3    0.24 *  69.7  15.7  54.0   9.5   9.4  32.3   2.8 *   14830
0.60   150    50    8025     18.0    0.31 *  69.7  15.7  54.0   9.5  10.1  32.4   2.0 *   14834
0.60   140    50    8025     16.7    0.30 *  70.2  15.7  54.5   9.5   9.4  33.3   2.2 *   14928
0.60   150    30   20861     10.9    0.19 *  70.4  15.7  54.7   9.5  10.1  31.7   3.4 *   14978
0.80   150    50    8025      9.9    0.26 *  70.6  12.4  58.2   7.8  10.1  36.6   3.6 *   15025
0.60   130    40   12181     12.3    0.23 *  70.6  15.7  54.9   9.5   8.8  33.6   3.1 *   15025
0.60   130    50    8025     15.4    0.29 *  70.8  15.7  55.1   9.5   8.8  34.3   2.5 *   15059
0.80   150    40   12181      7.9    0.21 *  71.3  12.4  58.9   7.8  10.1  36.4   4.6 *   15167
0.80   150    60    5707     11.9    0.32 *  71.5  12.4  59.1   7.8  10.1  38.1   3.1 *   15208
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                 JOB 4.  SAME AS JOB 3 BUT USE HYFLO SUPER-CEL AT
                         COST OF  $80/TON

             7 XI INDEX                  5.5E9    FT/LB
            16 DIATOMITE COST             80      $/TON
              BEGIN
           ____________________________________________________

FLOW  TERM   CO  B E T A   TIME  THICK * ----- COSTS, $ PER MILLION GALLONS ------ *   TOTAL
      HEAD         4  -2                *                         LAB+               *    COST
GSFM   FT   PPM  10 FT      HR      IN * TOTAL   1ST  OPER  MAIN  POWR  DIAT  BAKW *    $/MO
---------------------------------------*-------------------------------------------*--------

                   BETA INDEXES =  50 PERCENT OF PREDICTED VALUES
1.00   150   30    8436     9.8   0.23 *  49.6  10.4  39.2   6.8  10.1  20.2   2.1 *   10561
0.80   150   30    8436    15.6   0.26 *  49.7  12.4  37.3   7.8  10.1  18.0   1.4 *   10580
0.80   140   30    8436    14.5   0.25 *  49.8  12.4  37.4   7.8   9.4  18.6   1.5 *   10596
1.00   150   40    4926    13.1   0.31 *  49.9  10.4  39.4   6.8  10.1  20.9   1.6 *   10610
1.00   140   40    4926    12.2   0.29 *  49.9  10.4  39.5   6.8   9.4  21.5   1.8 *   10629
1.00   140   30    8436     9.1   0.22 *  50.0  10.4  39.5   6.8   9.4  21.0   2.4 *   10629
0.80   130   30    8436    13.4   0.24 *  50.0  12.4  37.6   7.8   8.8  19.4   1.7 *   10639
1.00   130   40    4926    11.2   0.28 *  50.2  10.4  39.7   6.8   8.8  22.2   2.0 *   10674
1.20   150   40    4926     9.0   0.27 *  50.3   9.1  41.2   6.1  10.1  22.6   2.4 *   10706
0.80   120   30    8436    12.3   0.23 *  50.3  12.4  37.9   7.8   8.1  20.2   1.9 *   10714

                   BETA INDEXES =  75 PERCENT OF PREDICTED VALUES
0.80   150   40    7389    13.5   0.28 *  54.8  12.4  42.4   7.8  10.1  22.6   1.8 *   11658
0.80   140   40    7389    12.5   0.26 *  55.0  12.4  42.6   7.8   9.4  23.3   2.0 *   11707
0.80   150   30   12654    10.1   0.21 *  55.1  12.4  42.7   7.8  10.1  22.3   2.5 *   11731
1.00   150   40    7389     8.5   0.24 *  55.4  10.4  44.9   6.8  10.1  25.1   2.9 *   11781
0.80   130   40    7389    11.5   0.25 *  55.4  12.4  43.0   7.8   8.8  24.2   2.3 *   11787
0.80   140   30   12654     9.4   0.20 *  55.6  12.4  43.2   7.8   9.4  23.3   2.7 *   11840
1.00   150   50    4868    10.6   0.31 *  55.7  10.4  45.3   6.8  10.1  26.1   2.4 *   11856
0.60   150   30   12654    18.3   0.24 *  55.8  15.7  40.1   9.5  10.1  19.1   1.4 *   11873
0.80   150   50    4868    17.1   0.36 *  55.8  12.4  43.4   7.8  10.1  24.0   1.5 *   11877
0.80   140   50    4868    15.8   0.34 *  55.9  12.4  43.5   7.8   9.4  24.6   1.6 *   11890

                   BETA INDEXES = 100 PERCENT OF PREDICTED VALUES
0.80   150   40    9852     9.9   0.24 *  59.1  12.4  46.7   7.8  10.1  26.0   2.8 *   12577
0.80   150   50    6491    12.4   0.30 *  59.3  12.4  46.9   7.8  10.1  26.7   2.3 *   12625
0.60   150   40    9852    18.0   0.28 *  59.5  15.7  43.8   9.5  10.1  22.6   1.6 *   12659
0.80   140   50    6491    11.5   0.29 *  59.7  12.4  47.3   7.8   9.4  27.5   2.5 *   12698
0.80   140   40    9852     9.2   0.23 *  59.7  12.4  47.3   7.8   9.4  26.9   3.1 *   12701
0.60   140   40    9852    16.7   0.26 *  59.7  15.7  44.0   9.5   9.4  23.3   1.8 *   12702
0.60   150   30   16872    13.5   0.21 *  59.7  15.7  44.1   9.5  10.1  22.3   2.2 *   12714
0.60   130   40    9852    15.4   0.25 *  60.0  15.7  44.4   9.5   8.8  24.1   2.0 *   12775
0.80   130   50    6491    10.6   0.27 *  60.2  12.4  47.8   7.8   8.8  28.4   2.8 *   12807
0.60   140   30   16872    12.6   0.20 *  60.2  15.7  44.5   9.5   9.4  23.2   2.4 *   12814

                   BETA INDEXES = 125 PERCENT OF PREDICTED VALUES
0.60   150   40   12315    14.1   0.24 *  62.6  15.7  46.9   9.5  10.1  25.1   2.2 *   13322
0.80   150   50    8113     9.7   0.26 *  63.0  12.4  50.5   7.8  10.1  29.5   3.1 *   13398
0.60   140   40   12315    13.1   0.23 *  63.1  15.7  47.4   9.5   9.4  26.0   2.4 *   13417
0.60   150   50    8113    17.8   0.31 *  63.1  15.7  47.4   9.5  10.1  26.0   1.8 *   13429
0.60   140   50    8113    16.5   0.30 *  63.3  15.7  47.7   9.5   9.4  26.8   2.0 *   13479
0.80   150   60    5769    11.8   0.32 *  63.6  12.4  51.2   7.8  10.1  30.6   2.6 *   13531
0.80   150   40   12315     7.8   0.21 *  63.6  12.4  51.2   7.8  10.1  29.3   4.0 *   13534
0.80   140   50    8113     9.0   0.25 *  63.6  12.4  51.2   7.8   9.4  30.5   3.5 *   13535
0.60   130   40   12315    12.2   0.23 *  63.7  15.7  48.0   9.5   8.8  27.0   2.7 *   13551
0.60   130   50    8113    15.2   0.28 *  63.7  15.7  48.1   9.5   8.8  27.6   2.2 *   13562

                   BETA INDEXES = 150 PERCENT OF PREDICTED VALUES
0.60   150   50    9736    14.6   0.28 *  65.7  15.7  50.0   9.5  10.1  28.1   2.3 *   13981
0.60   150   40   14778    11.7   0.22 *  65.8  15.7  50.1   9.5  10.1  27.6   2.9 *   14001
0.60   140   50    9736    13.5   0.27 *  66.1  15.7  50.5   9.5   9.4  29.0   2.5 *   14075
0.60   140   40   14778    10.8   0.22 *  66.5  15.7  50.8   9.5   9.4  28.7   3.2 *   14151
0.60   150   60    6923    17.7   0.34 *  66.7  15.7  51.0   9.5  10.1  29.4   2.0 *   14187
0.80   150   50    9736     8.0   0.24 *  66.7  12.4  54.3   7.8  10.1  32.3   4.1 *   14198
0.80   150   60    6923     9.6   0.29 *  66.7  12.4  54.3   7.8  10.1  33.0   3.5 *   14204
0.60   130   50    9736    12.5   0.26 *  66.8  15.7  51.1   9.5   8.8  30.0   2.8 *   14209
0.60   140   60    6923    16.3   0.33 *  66.9  15.7  51.3   9.5   9.4  30.2   2.1 *   14245
0.60   130   60    6923    15.1   0.31 *  67.4  15.7  51.7   9.5   8.8  31.1   2.4 *   14336

                   BETA INDEXES = 175 PERCENT OF PREDICTED VALUES
0.60   150   50   11359    12.3   0.25 *  68.4  15.7  52.7   9.5  10.1  30.2   2.9 *   14545
0.60   150   60    8077    14.9   0.31 *  68.9  15.7  53.2   9.5  10.1  31.2   2.4 *   14663
0.60   140   50   11359    11.5   0.24 *  69.0  15.7  53.3   9.5   9.4  31.2   3.2 *   14685
0.60   150   40   17241     9.9   0.21 *  69.1  15.7  53.4   9.5  10.1  30.1   3.7 *   14698
0.60   140   60    8077    13.8   0.30 *  69.4  15.7  53.7   9.5   9.4  32.1   2.7 *   14759
0.60   130   50   11359    10.6   0.24 *  69.9  15.7  54.2   9.5   8.8  32.4   3.6 *   14872
0.60   130   60    8077    12.7   0.28 *  70.0  15.7  54.3   9.5   8.8  33.1   3.0 *   14895
0.80   150   60    8077     8.2   0.26 *  70.0  12.4  57.6   7.8  10.1  35.3   4.4 *   14896
0.60   140   40   17241     9.2   0.20 *  70.0  15.7  54.4   9.5   9.4  31.4   4.1 *   14905
0.60   150   70    6054    17.6   0.38 *  70.2  15.7  54.5   9.5  10.1  32.8   2.1 *   14936
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                    JOB 5.  SAME AS JOB 4 EXCEPT FOR IRON CONCENTRATION

                 6 SOLIDS (CS)                    4    PPM IRON
                14 BODY FEED                20/5/70          PPM
                  BEGIN
             _____________________________________________________________

FLOW  TERM   CD  B E T A  TIME  THICK * ----- COSTS, $ PER MILLION GALLONS ------ *   TOTAL
      HEAD         4  -2                *                     LAB+                 *    COST
GSFM   FT   PPM  10 FT     HR      IN   * TOTAL   1ST  OPER  MAIN  POWR  DIAT  BAKW *    $/MO
------------------------------------------*------------------------------------------*--------

                        BETA INDEXES =  50 PERCENT OF PREDICTED VALUES
1.20   120   20    5557   12.4   0.23 *  37.8   9.1  28.7   6.1   8.1  13.4   1.2 *    8052
1.20   130   20    5557   13.5   0.24 *  37.8   9.1  28.7   6.1   8.8  12.8   1.0 *    8053
1.40   120   25    3661   11.2   0.26 *  37.9   8.2  29.7   5.7   8.1  14.7   1.3 *    8057
1.40   130   25    3661   12.3   0.27 *  37.9   8.2  29.7   5.7   8.8  14.2   1.1 *    8059
1.20   110   25    3661   14.1   0.27 *  37.9   9.1  28.8   6.1   7.4  14.2   1.0 *    8067
1.40   140   20    5557   10.6   0.23 *  37.9   8.2  29.8   5.7   9.4  13.4   1.3 *    8070
1.20   120   25    3661   15.5   0.29 *  37.9   9.1  28.8   6.1   8.1  13.7   0.9 *    8071
1.40   130   20    5557    9.8   0.22 *  37.9   8.2  29.8   5.7   8.8  13.9   1.4 *    8074
1.20   140   20    5557   14.6   0.25 *  38.0   9.1  28.8   6.1   9.4  12.4   0.9 *    8075
1.20   110   20    5557   11.3   0.22 *  38.0   9.1  28.9   6.1   7.4  14.0   1.3 *    8079

                        BETA INDEXES =  75 PERCENT OF PREDICTED VALUES
1.20   140   25    5492   11.8   0.25 *  41.4   9.1  32.2   6.1   9.4  15.4   1.3 *    8800
1.20   150   25    5492   12.7   0.26 *  41.4   9.1  32.3   6.1  10.1  14.9   1.2 *    8811
1.20   130   25    5492   10.9   0.24 *  41.4   9.1  32.3   6.1   8.8  16.0   1.5 *    8811
1.20   130   30    3905   13.1   0.29 *  41.5   9.1  32.4   6.1   8.8  16.3   1.2 *    8841
1.00   130   25    5492   16.0   0.26 *  41.6  10.4  31.1   6.8   8.8  14.6   1.0 *    8847
1.00   120   25    5492   14.6   0.25 *  41.6  10.4  31.1   6.8   8.1  15.2   1.1 *    8849
1.20   120   25    5492   10.0   0.23 *  41.6   9.1  32.5   6.1   8.1  16.6   1.7 *    8851
1.20   120   30    3905   12.0   0.28 *  41.6   9.1  32.5   6.1   8.1  16.9   1.4 *    8852
1.20   140   30    3905   14.3   0.30 *  41.6   9.1  32.5   6.1   9.4  15.8   1.1 *    8854
1.40   150   25    5492    9.3   0.24 *  41.7   8.2  33.5   5.7  10.1  16.0   1.7 *    8863

                        BETA INDEXES = 100 PERCENT OF PREDICTED VALUES
1.00   150   25    7323   13.7   0.24 *  44.2  10.4  33.8   6.8  10.1  15.6   1.3 *    9409
1.00   140   25    7323   12.7   0.24 *  44.2  10.4  33.8   6.8   9.4  16.2   1.4 *    9411
1.20   150   30    5207   11.2   0.27 *  44.3   9.1  35.2   6.1  10.1  17.4   1.5 *    9419
1.20   140   30    5207   10.4   0.26 *  44.3   9.1  35.2   6.1   9.4  18.0   1.7 *    9431
1.00   130   30    5207   14.1   0.27 *  44.3  10.4  33.9   6.8   8.8  17.1   1.3 *    9436
1.00   140   30    5207   15.3   0.28 *  44.3  10.4  33.9   6.8   9.4  16.5   1.2 *    9436
1.00   130   25    7323   11.7   0.23 *  44.3  10.4  33.9   6.8   8.8  16.8   1.5 *    9437
1.20   150   25    7323    9.4   0.22 *  44.4   9.1  35.3   6.1  10.1  17.2   1.9 *    9444
1.00   150   30    5207   16.5   0.30 *  44.4  10.4  34.0   6.8  10.1  16.1   1.1 *    9456
1.00   120   30    5207   12.9   0.26 *  44.5  10.4  34.0   6.8   8.1  17.7   1.4 *    9461

                        BETA INDEXES = 125 PERCENT OF PREDICTED VALUES
1.00   150   30    6509   12.9   0.26 *  46.5  10.4  36.1   6.8  10.1  17.7   1.5 *    9894
1.00   140   30    6509   12.0   0.25 *  46.6  10.4  36.1   6.8   9.4  18.3   1.6 *    9908
1.00   150   25    9154   10.8   0.22 *  46.7  10.4  36.2   6.8  10.1  17.6   1.8 *    9927
1.00   130   30    6509   11.1   0.24 *  46.8  10.4  36.3   6.8   8.8  19.0   1.8 *    9949
1.00   140   35    4879   14.1   0.30 *  46.8  10.4  36.4   6.8   9.4  18.8   1.4 *    9958
1.00   150   35    4879   15.2   0.31 *  46.8  10.4  36.4   6.8  10.1  18.3   1.3 *    9964
1.00   140   25    9154   10.0   0.21 *  46.9  10.4  36.4   6.8   9.4  18.3   1.9 *    9971
1.20   150   30    6509    8.9   0.24 *  46.9   9.1  37.7   6.1  10.1  19.4   2.1 *    9971
1.00   130   35    4879   13.0   0.28 *  46.9  10.4  36.4   6.8   8.8  19.4   1.5 *    9974
1.20   150   35    4879   10.3   0.28 *  46.9   9.1  37.8   6.1  10.1  19.7   1.8 *    9974

                        BETA INDEXES = 150 PERCENT OF PREDICTED VALUES
1.00   150   30    7811   10.6   0.24 *  48.6  10.4  38.2   6.8  10.1  19.4   1.9 *   10342
1.00   150   35    5855   12.4   0.28 *  48.7  10.4  38.2   6.8  10.1  19.7   1.6 *   10353
1.00   140   35    5855   11.5   0.27 *  48.8  10.4  38.3   6.8   9.4  20.3   1.8 *   10377
1.00   140   30    7811    9.9   0.23 *  48.8  10.4  38.4   6.8   9.4  20.1   2.1 *   10393
0.80   150   30    7811   16.9   0.27 *  48.9  12.4  36.5   7.8  10.1  17.4   1.2 *   10415
0.80   140   30    7811   15.7   0.26 *  49.0  12.4  36.5   7.8   9.4  18.0   1.3 *   10418
0.80   150   25   10985   14.1   0.22 *  49.0  12.4  36.6   7.8  10.1  17.2   1.5 *   10424
1.00   130   35    5855   10.6   0.25 *  49.0  10.4  38.6   6.8   8.8  21.1   2.0 *   10429
1.00   150   40    4561   14.3   0.32 *  49.1  10.4  38.6   6.8  10.1  20.3   1.4 *   10443
0.80   130   30    7811   14.5   0.25 *  49.1  12.4  36.7   7.8   8.8  18.6   1.5 *   10445

                        BETA INDEXES = 175 PERCENT OF PREDICTED VALUES
1.00   150   35    6831   10.5   0.25 *  50.5  10.4  40.1   6.8  10.1  21.2   2.1 *   10749
0.80   150   30    9113   14.3   0.24 *  50.6  12.4  38.2   7.8  10.1  18.7   1.5 *   10761
0.80   140   30    9113   13.3   0.24 *  50.7  12.4  38.3   7.8   9.4  19.4   1.7 *   10792
1.00   150   40    5321   12.1   0.29 *  50.7  10.4  40.3   6.8  10.1  21.6   1.8 *   10796
1.00   150   30    9113    9.0   0.22 *  50.8  10.4  40.3   6.8  10.1  21.1   2.4 *   10801
0.80   150   35    6831   16.8   0.29 *  50.8  12.4  38.3   7.8  10.1  19.1   1.3 *   10802
1.00   140   35    6831    9.8   0.24 *  50.8  10.4  40.3   6.8   9.4  21.9   2.3 *   10806
0.80   140   35    6831   15.5   0.28 *  50.8  12.4  38.4   7.8   9.4  19.7   1.4 *   10810
1.00   140   40    5321   11.2   0.28 *  50.9  10.4  40.4   6.8   9.4  22.3   2.0 *   10827
0.80   150   25   12816   12.0   0.21 *  50.9  12.4  38.5   7.8  10.1  18.7   1.8 *   10835
```

```
P O P O -- PROGRAM FOR OPTIMIZATION OF PLANT OPERATION

      JOB 6.  KENTUCKY BALL CLAY

  1 DESIGN FLOW                  3       MGD
  2 SALVAGE VALUE               15       PERCENT FIRST COST
  3 ENERGY CONVERSION           70       PERCENT
  4 INTEREST RATE                4       PERCENT
  5 PLANT LIFE                  15       YEARS
  6 SOLIDS  (CS)                50       PPM CLAY (TURBIDITY)
  7 XI INDEX                 5.1E9       FT/LB
  8 TEMPERATURE                 48       DEGREES F
  9 PRECOAT WEIGHT             0.1       LB/SF
 10 PRECOAT DENSITY             15       LB/CF
 11 SEPTUM DIAMETER              1       INCHES
 12 BETA PREDICTION     3.43/1.96/-0.254/0.491
 13 UNIT FLOW RATE       0.5/0.5/2                  GSFM
 14 BODY FEED             40/10/100                 PPM
 15 TERMINAL HEAD         75/15/150                 FT
 16 DIATOMITE COST              80    $/TON
 17 FIRST COST               AREA       $/SF
                              100        225
                              200        160
                              350        128
                              600        110
                             1000        100
                             2000         94
   *                        25000         85
 18 POWER COST                  1.5   CENTS/KWH
 19 LABOR COST               AREA       $/SF PER MONTH
                              100        2.00
                              200 1.15 →
                              300        0.83
                              500        0.63
                              800        0.50
                             2000        0.37
   *                         4500        0.30
 20 BACKWASH COST             10, 30  GAL/SF, MIN
   BEGIN
```

```
                                          JOB 6

FLOW  TERM    CD   B E T A  TIME   THICK * ----- COSTS, $ PER MILLION GALLONS ------ *   TOTAL
      HEAD           4  -2                 *                     LAB+                  *    COST
GSFM   FT    PPM   10 FT     HR      IN  * TOTAL   1ST  OPER   MAIN  POWR  DIAT  BAKW *    $/MO
-----------------------------------------*----------------------------------------------*--------

                                BETA INDEXES =  50 PERCENT OF PREDICTED VALUES
1.50   150    40     4768     7.2    0.21 *  50.4  11.2  39.2    7.0  10.1  19.5    2.6 *     4598
1.50   135    40     4768     6.3    0.20 *  50.7  11.2  39.5    7.0   9.1  20.4    3.1 *     4626
1.50   135    50     2909     9.4    0.29 *  50.7  11.2  39.5    7.0   9.1  21.4    2.1 *     4626
1.50   150    50     2909    10.9    0.31 *  50.8  11.2  39.6    7.0  10.1  20.8    1.8 *     4631
1.00   120    40     4768    13.5    0.24 *  50.9  14.7  36.2    8.4   8.1  18.3    1.5 *     4644
1.50   120    50     2909     8.0    0.26 *  50.9  11.2  39.8    7.0   8.1  22.2    2.5 *     4645
1.00   135    40     4768    15.7    0.27 *  51.0  14.7  36.3    8.4   9.1  17.6    1.2 *     4651
1.00   105    40     4768    11.4    0.22 *  51.1  14.7  36.4    8.4   7.1  19.2    1.8 *     4664
1.00   150    40     4768    18.1    0.29 *  51.3  14.7  36.5    8.4  10.1  17.0    1.1 *     4676
1.50   120    40     4768     5.5    0.18 *  51.4  11.2  40.2    7.0   8.1  21.4    3.7 *     4687

                                BETA INDEXES =  75 PERCENT OF PREDICTED VALUES
1.00   150    40     7153    10.8    0.21 *  54.7  14.7  40.0    8.4  10.1  19.5    2.0 *     4989
1.00   135    40     7153     9.5    0.20 *  54.9  14.7  40.1    8.4   9.1  20.4    2.3 *     5005
1.00   135    50     4364    14.1    0.29 *  55.1  14.7  40.4    8.4   9.1  21.4    1.6 *     5029
1.00   120    50     4364    12.1    0.26 *  55.2  14.7  40.5    8.4   8.1  22.2    1.9 *     5038
1.50   150    50     4364     6.4    0.23 *  55.3  11.2  44.1    7.0  10.1  23.6    3.4 *     5041
1.00   150    50     4364    16.3    0.31 *  55.3  14.7  40.6    8.4  10.1  20.7    1.3 *     5042
1.00   120    40     7153     8.2    0.18 *  55.4  14.7  40.6    8.4   8.1  21.4    2.8 *     5050
1.50   150    60     2914     9.0    0.31 *  55.6  11.2  44.4    7.0  10.1  24.9    2.4 *     5073
1.00   105    50     4364    10.2    0.24 *  55.7  14.7  41.0    8.4   7.1  23.2    2.3 *     5078
1.50   135    60     2914     7.8    0.29 *  55.8  11.2  44.7    7.0   9.1  25.7    2.9 *     5092

                                BETA INDEXES = 100 PERCENT OF PREDICTED VALUES
1.00   150    50     5819    11.2    0.25 *  58.0  14.7  43.2    8.4  10.1  22.6    2.1 *     5286
1.00   135    50     5819     9.8    0.23 *  58.2  14.7  43.4    8.4   9.1  23.5    2.5 *     5305
1.00   150    40     9537     7.7    0.18 *  58.4  14.7  43.6    8.4  10.1  22.0    3.1 *     5322
1.00   120    50     5819     8.4    0.21 *  58.7  14.7  44.0    8.4   8.1  24.6    3.0 *     5355
1.00   135    60     3886    13.8    0.32 *  58.8  14.7  44.1    8.4   9.1  24.8    1.8 *     5363
1.00   150    60     3886    16.0    0.35 *  58.9  14.7  44.1    8.4  10.1  24.2    1.5 *     5369
1.00   120    60     3886    11.8    0.29 *  59.0  14.7  44.3    8.4   8.1  25.7    2.2 *     5381
1.00   135    40     9537     6.8    0.17 *  59.0  14.7  44.3    8.4   9.1  23.2    3.7 *     5383
1.50   150    60     3886     6.2    0.25 *  59.4  11.2  48.2    7.0  10.1  27.2    3.9 *     5417
1.00   105    60     3886     9.9    0.26 *  59.6  14.7  44.9    8.4   7.1  26.8    2.7 *     5435

                                BETA INDEXES = 125 PERCENT OF PREDICTED VALUES
1.00   150    50     7274     8.4    0.21 *  60.8  14.7  46.0    8.4  10.1  24.6    3.0 *     5542
1.00   150    60     4858    11.8    0.27 *  61.1  14.7  46.3    8.4  10.1  25.7    2.2 *     5567
1.00   135    60     4858    10.2    0.26 *  61.3  14.7  46.5    8.4   9.1  26.5    2.6 *     5588
1.00   135    50     7274     7.4    0.20 *  61.4  14.7  46.6    8.4   9.1  25.6    3.5 *     5596
1.00   120    60     4858     8.8    0.24 *  61.9  14.7  47.1    8.4   8.1  27.6    3.1 *     5640
1.00   135    70     3453    14.0    0.35 *  62.2  14.7  47.5    8.4   9.1  28.1    1.9 *     5675
1.00   150    40    11921     5.9    0.16 *  62.2  14.7  47.5    8.4  10.1  24.6    4.5 *     5675
1.00   150    70     3453    16.3    0.39 *  62.2  14.7  47.5    8.4  10.1  27.4    1.6 *     5676
1.00   120    50     7274     6.5    0.18 *  62.4  14.7  47.7    8.4   8.1  27.0    4.3 *     5691
1.00   120    70     3453    11.8    0.32 *  62.5  14.7  47.8    8.4   8.1  29.0    2.3 *     5698

                                BETA INDEXES = 150 PERCENT OF PREDICTED VALUES
1.00   150    60     5829     9.3    0.25 *  63.3  14.7  48.6    8.4  10.1  27.2    2.9 *     5774
1.00   150    50     8729     6.8    0.19 *  63.7  14.7  49.0    8.4  10.1  26.5    4.0 *     5810
1.00   135    60     5829     8.1    0.23 *  63.9  14.7  49.1    8.4   9.1  28.2    3.5 *     5823
1.00   150    70     4144    12.5    0.33 *  64.1  14.7  49.3    8.4  10.1  28.6    2.2 *     5842
1.00   135    70     4144    10.8    0.30 *  64.3  14.7  49.6    8.4   9.1  29.5    2.6 *     5863
1.00   135    50     8729     6.0    0.18 *  64.7  14.7  50.0    8.4   9.1  27.8    4.8 *     5901
1.00   120    60     5829     7.0    0.21 *  64.8  14.7  50.1    8.4   8.1  29.5    4.2 *     5912
1.00   120    70     4144     9.3    0.27 *  64.9  14.7  50.1    8.4   8.1  30.5    3.2 *     5916
1.00   150    80     3083    17.0    0.44 *  65.5  14.7  50.8    8.4  10.1  30.6    1.7 *     5972
1.00   135    80     3083    14.4    0.39 *  65.5  14.7  50.8    8.4   9.1  31.3    2.0 *     5973

                                BETA INDEXES = 175 PERCENT OF PREDICTED VALUES
1.00   150    60     6801     7.6    0.22 *  65.7  14.7  50.9    8.4  10.1  28.7    3.8 *     5989
1.00   150    70     4834    10.2    0.29 *  66.0  14.7  51.2    8.4  10.1  29.9    2.9 *     6014
1.00   135    70     4834     8.8    0.26 *  66.4  14.7  51.7    8.4   9.1  30.9    3.4 *     6059
1.00   135    60     6801     6.7    0.21 *  66.5  14.7  51.8    8.4   9.1  29.9    4.4 *     6068
1.00   150    50    10183     5.7    0.17 *  66.8  14.7  52.0    8.4  10.1  28.4    5.2 *     6090
1.00   150    80     3597    13.4    0.38 *  67.0  14.7  52.3    8.4  10.1  31.6    2.2 *     6113
1.00   135    80     3597    11.5    0.34 *  67.3  14.7  52.5    8.4   9.1  32.4    2.6 *     6134
1.00   120    70     4834     7.6    0.24 *  67.4  14.7  52.6    8.4   8.1  32.1    4.1 *     6143
1.00   120    80     3597     9.8    0.31 *  67.8  14.7  53.1    8.4   8.1  33.5    3.2 *     6187
1.00   120    60     6801     5.8    0.19 *  67.9  14.7  53.2    8.4   8.1  31.4    5.3 *     6196
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                    JOB 7.  SAME AS JOB 6 EXCEPT FOR TEMPERATURE

                 8 TEMPERATURE                    72    DEGREES F
                  BEGIN

               ----------------------------------------------------

FLOW  TERM   CD   B E T A   TIME  THICK * ----- COSTS, $ PER MILLION GALLONS ------ *    TOTAL
      HEAD          4  -2                *                         LAB+             *     COST
GSFM   FT   PPM   10 FT      HR     IN   * TOTAL   1ST  OPER  MAIN  POWR  DIAT  BAKW *     $/MO
-----------------------------------------*------------------------------------------*---------

                             BETA INDEXES =  50 PERCENT OF PREDICTED VALUES
1.50   135   40      4768    9.7   0.25 *  47.0  11.2  35.8   7.0   9.1  17.9   1.8 *     4282
1.50   120   40      4768    8.3   0.23 *  47.0  11.2  35.9   7.0   8.1  18.7   2.1 *     4290
1.50   150   40      4768   11.1   0.28 *  47.1  11.2  35.9   7.0  10.1  17.3   1.5 *     4296
1.50   105   40      4768    7.1   0.21 *  47.5  11.2  36.3   7.0   7.1  19.6   2.6 *     4330
1.50   120   50      2909   12.9   0.35 *  47.8  11.2  36.6   7.0   8.1  20.1   1.4 *     4357
1.50   105   50      2909   10.7   0.31 *  47.8  11.2  36.6   7.0   7.1  20.8   1.8 *     4361
2.00   150   40      4768    5.8   0.22 *  47.9   9.4  38.5   6.3  10.1  19.1   3.0 *     4365
1.50   135   50      2909   15.3   0.39 *  48.0  11.2  36.8   7.0   9.1  19.6   1.2 *     4377
2.00   135   50      2909    7.6   0.30 *  48.2   9.4  38.8   6.3   9.1  21.0   2.4 *     4392
2.00   135   40      4768    5.1   0.21 *  48.2   9.4  38.8   6.3   9.1  19.9   3.5 *     4395

                             BETA INDEXES =  75 PERCENT OF PREDICTED VALUES
1.50   150   40      7153    6.7   0.20 *  51.1  11.2  40.0   7.0  10.1  20.0   2.9 *     4664
1.50   150   50      4364   10.0   0.30 *  51.3  11.2  40.1   7.0  10.1  21.1   1.9 *     4679
1.50   135   50      4364    8.7   0.27 *  51.3  11.2  40.1   7.0   9.1  21.8   2.3 *     4680
1.00   120   40      7153   12.5   0.23 *  51.5  14.7  36.7   8.4   8.1  18.6   1.6 *     4692
1.00   135   40      7153   14.6   0.25 *  51.5  14.7  36.7   8.4   9.1  17.9   1.4 *     4693
1.50   135   40      7153    5.9   0.19 *  51.5  11.2  40.4   7.0   9.1  20.9   3.4 *     4700
1.50   120   50      4364    7.5   0.25 *  51.6  11.2  40.4   7.0   8.1  22.6   2.8 *     4708
1.00   150   40      7153   16.7   0.28 *  51.7  14.7  37.0   8.4  10.1  17.3   1.2 *     4714
1.00   105   40      7153   10.6   0.21 *  51.8  14.7  37.0   8.4   7.1  19.6   2.0 *     4720
1.00   105   50      4364   16.1   0.31 *  52.3  14.7  37.6   8.4   7.1  20.8   1.3 *     4771

                             BETA INDEXES = 100 PERCENT OF PREDICTED VALUES
1.00   150   40      9537   11.6   0.22 *  54.1  14.7  39.4   8.4  10.1  19.1   1.8 *     4935
1.00   135   40      9537   10.2   0.21 *  54.2  14.7  39.5   8.4   9.1  19.9   2.1 *     4943
1.50   150   50      5819    6.9   0.24 *  54.5  11.2  43.3   7.0  10.1  23.1   3.1 *     4968
1.00   120   40      9537    8.8   0.19 *  54.6  14.7  39.9   8.4   8.1  20.9   2.5 *     4979
1.00   135   50      5819   15.3   0.30 *  54.6  14.7  39.9   8.4   9.1  21.0   1.4 *     4983
1.00   120   50      5819   13.1   0.27 *  54.7  14.7  39.9   8.4   8.1  21.8   1.7 *     4985
1.00   150   50      5819   17.7   0.33 *  54.9  14.7  40.1   8.4  10.1  20.4   1.2 *     5002
1.50   135   50      5819    6.0   0.22 *  54.9  11.2  43.7   7.0   9.1  24.0   3.6 *     5010
1.00   105   50      5819   11.0   0.25 *  55.0  14.7  40.3   8.4   7.1  22.7   2.1 *     5017
1.50   150   60      3886    9.8   0.33 *  55.0  11.2  43.8   7.0  10.1  24.5   2.2 *     5017

                             BETA INDEXES = 125 PERCENT OF PREDICTED VALUES
1.00   150   40     11921    8.8   0.19 *  56.7  14.7  41.9   8.4  10.1  20.9   2.6 *     5166
1.00   150   50      7274   13.1   0.27 *  56.7  14.7  42.0   8.4  10.1  21.8   1.7 *     5171
1.00   135   50      7274   11.4   0.25 *  56.8  14.7  42.0   8.4   9.1  22.5   2.1 *     5175
1.00   135   40     11921    7.8   0.18 *  57.1  14.7  42.3   8.4   9.1  21.9   3.0 *     5205
1.00   120   50      7274    9.8   0.23 *  57.1  14.7  42.3   8.4   8.1  23.4   2.5 *     5206
1.50   150   60      4858    7.2   0.27 *  57.6  11.2  46.4   7.0  10.1  26.1   3.2 *     5254
1.00   135   60      4858   16.4   0.35 *  57.7  14.7  43.0   8.4   9.1  24.1   1.5 *     5263
1.00   120   60      4858   13.9   0.32 *  57.7  14.7  43.0   8.4   8.1  24.8   1.8 *     5266
1.00   105   50      7274    8.3   0.21 *  57.8  14.7  43.1   8.4   7.1  24.7   3.0 *     5275
1.50   150   50      7274    5.2   0.20 *  57.9  11.2  46.7   7.0  10.1  25.2   4.4 *     5277

                             BETA INDEXES = 150 PERCENT OF PREDICTED VALUES
1.00   150   50      8729   10.3   0.24 *  58.6  14.7  43.9   8.4  10.1  23.1   2.3 *     5348
1.00   135   50      8729    9.1   0.22 *  58.9  14.7  44.2   8.4   9.1  24.0   2.7 *     5375
1.00   150   40     14306    7.1   0.17 *  59.3  14.7  44.6   8.4  10.1  22.7   3.4 *     5407
1.00   150   60      5829   14.7   0.33 *  59.4  14.7  44.7   8.4  10.1  24.5   1.7 *     5417
1.00   135   60      5829   12.7   0.30 *  59.4  14.7  44.7   8.4   9.1  25.2   2.0 *     5417
1.00   120   50      8729    7.9   0.20 *  59.6  14.7  44.9   8.4   8.1  25.1   3.3 *     5435
1.00   120   60      5829   10.9   0.27 *  59.7  14.7  45.0   8.4   8.1  26.1   2.4 *     5443
1.00   135   40     14306    6.3   0.16 *  60.1  14.7  45.3   8.4   9.1  23.9   4.0 *     5479
1.50   150   60      5829    5.7   0.24 *  60.4  11.2  49.2   7.0  10.1  27.8   4.3 *     5504
1.00   105   60      5829    9.1   0.25 *  60.4  14.7  45.7   8.4   7.1  27.3   2.9 *     5507

                             BETA INDEXES = 175 PERCENT OF PREDICTED VALUES
1.00   150   50     10183    8.5   0.21 *  60.6  14.7  45.9   8.4  10.1  24.5   3.0 *     5530
1.00   150   60      6801   11.9   0.29 *  60.9  14.7  46.2   8.4  10.1  25.6   2.2 *     5558
1.00   135   60      6801   10.4   0.27 *  61.2  14.7  46.4   8.4   9.1  26.4   2.5 *     5577
1.00   135   50     10183    7.5   0.20 *  61.2  14.7  46.5   8.4   9.1  25.5   3.5 *     5582
1.00   120   60      6801    8.9   0.24 *  61.7  14.7  47.0   8.4   8.1  27.5   3.0 *     5627
1.00   150   40     16690    6.0   0.16 *  62.0  14.7  47.3   8.4  10.1  24.5   4.4 *     5658
1.00   135   70      4834   14.2   0.36 *  62.1  14.7  47.4   8.4   9.1  28.0   1.9 *     5666
1.00   150   70      4834   16.5   0.39 *  62.2  14.7  47.4   8.4  10.1  27.4   1.6 *     5669
1.00   120   50     10183    6.5   0.18 *  62.2  14.7  47.5   8.4   8.1  26.9   4.2 *     5674
1.00   120   70      4834   12.0   0.32 *  62.4  14.7  47.6   8.4   8.1  28.9   2.3 *     5688
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                    JOB 8.  JOB 7 EXCEPT WYOMING BENTONITE AND FOLLOWING

                  6 SOLIDS                      30    PPM CLAY (TURBIDITY)
                 12 BETA PREDICTION      11.81/1.58/-1.06/0
                 13 UNIT FLOW RATE         0.3/0.2/1.1          GSFM
                 14 BODY FEED             200/10/300            PPM
                   BEGIN
               ______________________________________________________________

FLOW  TERM   CD  B E T A  TIME  THICK * ----- COSTS, $ PER MILLION GALLONS ------ *   TOTAL
      HEAD        4  -2                 *                        LAB+                *    COST
GSFM   FT   PPM  10 FT     HR      IN  * TOTAL    1ST  OPER  MAIN  POWR  DIAT  BAKW *    $/MO
---------------------------------------*--------------------------------------------*---------

                               BETA INDEXES =  50 PERCENT OF PREDICTED VALUES
0.70   150  200     5862   10.7   0.47 * 122.0   19.5 102.5  10.2  10.1  75.6   6.6 *   11128
0.50   150  200     5862   26.7   0.69 * 123.0   25.8  97.2  12.6  10.1  71.6   2.8 *   11213
0.70   150  210     5154   12.5   0.54 * 123.1   19.5 103.6  10.2  10.1  77.6   5.7 *   11226
0.50   135  200     5862   22.0   0.60 * 123.7   25.8  97.9  12.6   9.1  72.7   3.5 *   11277
0.70   135  200     5862    9.0   0.42 * 124.0   19.5 104.5  10.2   9.1  77.2   8.0 *   11309
0.70   150  220     4558   14.8   0.62 * 124.4   19.5 104.9  10.2  10.1  79.7   4.9 *   11349
0.70   135  210     5154   10.5   0.48 * 124.8   19.5 105.3  10.2   9.1  79.0   6.9 *   11378
0.50   120  200     5862   18.0   0.53 * 124.9   25.8  99.1  12.6   8.1  74.1   4.4 *   11389
0.50   150  210     5154   32.7   0.81 * 124.9   25.8  99.1  12.6  10.1  74.0   2.4 *   11390
0.50   135  210     5154   26.6   0.71 * 125.4   25.8  99.6  12.6   9.1  75.0   2.9 *   11437

                               BETA INDEXES =  75 PERCENT OF PREDICTED VALUES
0.50   150  200     8794   13.4   0.43 * 131.2   25.8 105.4  12.6  10.1  76.6   6.2 *   11968
0.50   150  210     7731   15.7   0.50 * 132.3   25.8 106.5  12.6  10.1  78.5   5.3 *   12065
0.50   135  200     8794   11.4   0.39 * 133.2   25.8 107.4  12.6   9.1  78.3   7.4 *   12148
0.50   150  220     6837   18.4   0.57 * 133.6   25.8 107.8  12.6  10.1  80.6   4.6 *   12187
0.50   135  210     7731   13.2   0.44 * 134.0   25.8 108.2  12.6   9.1  80.0   6.4 *   12218
0.50   135  220     6837   15.4   0.51 * 135.0   25.8 109.3  12.6   9.1  82.0   5.6 *   12316
0.50   150  230     6080   21.7   0.66 * 135.2   25.8 109.4  12.6  10.1  82.8   4.0 *   12332
0.50   120  200     8794    9.6   0.35 * 136.1   25.8 110.3  12.6   8.1  80.5   9.1 *   12409
0.70   150  210     7731    6.7   0.35 * 136.1   19.5 116.6  10.2  10.1  84.2  12.0 *   12411
0.70   150  220     6837    7.6   0.40 * 136.2   19.5 116.7  10.2  10.1  85.8  10.5 *   12417

                               BETA INDEXES = 100 PERCENT OF PREDICTED VALUES
0.50   150  200    11725    8.8   0.33 * 140.6   25.8 114.8  12.6  10.1  81.8  10.3 *   12820
0.50   150  210    10308   10.0   0.37 * 140.7   25.8 114.9  12.6  10.1  83.2   9.0 *   12832
0.50   150  220     9117   11.5   0.42 * 141.2   25.8 115.4  12.6  10.1  84.9   7.9 *   12880
0.50   150  230     8107   13.2   0.47 * 142.1   25.8 116.3  12.6  10.1  86.7   6.9 *   12959
0.50   150  240     7245   15.3   0.53 * 143.2   25.8 117.4  12.6  10.1  88.7   6.1 *   13064
0.50   135  210    10308    8.6   0.34 * 143.7   25.8 117.9  12.6   9.1  85.4  10.8 *   13101
0.50   135  220     9117    9.8   0.38 * 143.8   25.8 118.0  12.6   9.1  86.9   9.5 *   13116
0.50   135  200    11725    7.6   0.30 * 144.0   25.8 118.2  12.6   9.1  84.2  12.3 *   13128
0.50   135  230     8107   11.2   0.42 * 144.4   25.8 118.6  12.6   9.1  88.5   8.4 *   13164
0.50   150  250     6505   17.7   0.60 * 144.6   25.8 118.8  12.6  10.1  90.8   5.3 *   13191

                               BETA INDEXES = 125 PERCENT OF PREDICTED VALUES
0.50   150  220    11396    8.3   0.34 * 149.6   25.8 123.8  12.6  10.1  89.4  11.7 *   13641
0.50   150  230    10134    9.4   0.38 * 149.7   25.8 123.9  12.6  10.1  90.8  10.4 *   13650
0.50   150  210    12885    7.3   0.30 * 149.9   25.8 124.1  12.6  10.1  88.1  13.3 *   13672
0.50   150  240     9057   10.7   0.42 * 150.1   25.8 124.3  12.6  10.1  92.5   9.2 *   13693
0.50   150  200    14656    6.5   0.27 * 150.8   25.8 125.0  12.6  10.1  87.2  15.1 *   13751
0.50   150  250     8132   12.1   0.47 * 150.9   25.8 125.1  12.6  10.1  94.3   8.2 *   13764
0.30   150  200    14656   22.4   0.43 * 151.6   40.3 111.4  19.6  10.1  76.6   5.0 *   13826
0.50   150  260     7332   13.8   0.53 * 152.0   25.8 126.2  12.6  10.1  96.3   7.2 *   13861
0.30   150  210    12885   26.1   0.50 * 152.8   40.3 112.6  19.6  10.1  78.5   4.3 *   13937
0.50   135  230    10134    8.1   0.34 * 153.1   25.8 127.3  12.6   9.1  93.1  12.5 *   13962

                               BETA INDEXES = 150 PERCENT OF PREDICTED VALUES
0.30   150  200    17588   17.0   0.36 * 156.6   40.3 116.4  19.6  10.1  79.7   6.9 *   14283
0.30   150  210    15462   19.6   0.41 * 157.3   40.3 117.1  19.6  10.1  81.3   6.0 *   14349
0.50   150  240    10868    8.1   0.35 * 157.6   25.8 131.8  12.6  10.1  96.3  12.8 *   14372
0.50   150  250     9758    9.2   0.39 * 157.7   25.8 132.0  12.6  10.1  97.9  11.4 *   14386
0.50   150  230    12161    7.3   0.32 * 157.8   25.8 132.0  12.6  10.1  95.0  14.3 *   14395
0.50   150  260     8798   10.3   0.43 * 158.2   25.8 132.4  12.6  10.1  99.6  10.2 *   14431
0.30   150  220    13675   22.7   0.47 * 158.4   40.3 118.1  19.6  10.1  83.1   5.3 *   14444
0.50   150  220    13675    6.5   0.29 * 158.6   25.8 132.8  12.6  10.1  93.9  16.1 *   14460
0.50   150  270     7964   11.6   0.48 * 159.0   25.8 133.2  12.6  10.1 101.4   9.1 *   14502
0.30   135  200    17588   14.6   0.33 * 159.0   40.3 118.8  19.6   9.1  81.8   8.2 *   14504

                               BETA INDEXES = 175 PERCENT OF PREDICTED VALUES
0.30   150  200    20519   13.7   0.32 * 161.9   40.3 121.6  19.6  10.1  82.9   9.0 *   14762
0.30   150  210    18039   15.6   0.35 * 162.1   40.3 121.8  19.6  10.1  84.2   7.9 *   14782
0.30   150  220    15954   17.9   0.40 * 162.7   40.3 122.4  19.6  10.1  85.8   6.9 *   14837
0.30   150  230    14188   20.4   0.45 * 163.6   40.3 123.4  19.6  10.1  87.5   6.1 *   14921
0.30   150  240    12680   23.5   0.51 * 164.8   40.3 124.6  19.6  10.1  89.4   5.4 *   15030
0.30   135  210    18039   13.5   0.32 * 164.9   40.3 124.6  19.6   9.1  86.5   9.4 *   15036
0.50   150  260    10265    8.2   0.37 * 164.9   25.8 139.1  12.6  10.1 103.0  13.5 *   15040
0.50   150  250    11384    7.3   0.34 * 165.0   25.8 139.2  12.6  10.1 101.5  15.0 *   15050
0.30   135  200    20519   11.9   0.29 * 165.1   40.3 124.8  19.6   9.1  85.4  10.7 *   15052
0.30   135  220    15954   15.3   0.36 * 165.1   40.3 124.9  19.6   9.1  87.8   8.3 *   15060
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P O P O -- PROGRAM FOR OPTIMIZATION OF PLANT OPERATION

       JOB 9.  SOFTENING, LOMPOC PLANT (OPERATING COSTS)

   1 DESIGN FLOW                 4.5   MGD
   2 SALVAGE VALUE               15    PERCENT FIRST COST
   3 ENERGY CONVERSION           70    PERCENT
   4 INTEREST RATE                4    PERCENT
   5 PLANT LIFE                  30    YEARS
   6 SOLIDS  (CS)                8.5   PPM
   7 XI INDEX                  1.95E9  FT/LB
   8 TEMPERATURE                 65    DEGREES F
   9 PRECOAT WEIGHT              0.1   LB/SF
  10 PRECOAT DENSITY             15    LB/CF
  11 SEPTUM DIAMETER            FLAT   INCHES
  12 BETA PREDICTION      10.2/1.43/-1.86/0
  13 UNIT FLOW RATE             0.73             GSFM
  14 BODY FEED                10/2/30            PPM
  15 TERMINAL HEAD               25              FT
  16 DIATOMITE COST               69    $/TON
  17 FIRST COST                AREA     $/SF
                                100      225
                                200      160
                                300      128
                                600      110
                               1000      100
                               2000       94
   .                          25000       85
  18 POWER COST                    1   CENTS/KWH
  19 LABOR COST                AREA    $/SF PER MONTH
                                100     2.00
                                200     1.15
                                300     0.83
                                500     0.63
                                800     0.50
                               2000     0.37
                               4500     0.30
                              13000     0.25
   .                          25000     0.24
  20 BACKWASH COST             6, 30   GAL/SF, MIN
    BEGIN
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                                            JOB 9

FLOW  TERM   CD  B E T A  TIME  THICK * ----- COSTS, $ PER MILLION GALLONS ------ *   TOTAL
      HEAD         4  -2                *                      LAB+                *    COST
GSFM   FT   PPM  10 FT      HR     IN  * TOTAL   1ST  OPER   MAIN  POWR  DIAT  BAKW *    $/MO
---------------------------------------*-------------------------------------------*--------

                                BETA INDEXES =  50 PERCENT OF PREDICTED VALUES
0.73    25   20     886   41.9   0.32 *  30.4  12.4  18.0    9.0   1.1   7.6   0.3 *    4161
0.73    25   18    1253   32.9   0.25 *  30.4  12.4  18.0    9.0   1.1   7.6   0.3 *    4163
0.73    25   22     647   52.1   0.41 *  30.6  12.4  18.2    9.0   1.1   7.8   0.2 *    4183
0.73    25   16    1847   25.1   0.20 *  30.7  12.4  18.3    9.0   1.1   7.7   0.4 *    4201
0.73    25   24     486   63.6   0.53 *  30.8  12.4  18.4    9.0   1.1   8.1   0.2 *    4219
0.73    25   26     373   76.4   0.66 *  31.2  12.4  18.8    9.0   1.1   8.5   0.1 *    4266
0.73    25   14    2866   18.5   0.16 *  31.4  12.4  19.0    9.0   1.1   8.3   0.6 *    4300
0.73    25   28     293   90.5   0.82 *  31.6  12.4  19.2    9.0   1.1   8.9   0.1 *    4320
0.73    25   30     233  106.0   1.01 *  32.0  12.4  19.6    9.0   1.1   9.4   0.1 *    4379
0.73    25   12    4759   13.0   0.13 *  33.0  12.4  20.6    9.0   1.1   9.5   1.0 *     515

                                BETA INDEXES =  75 PERCENT OF PREDICTED VALUES
0.73    25   22     971   34.7   0.30 *  31.5  12.4  19.0    9.0   1.1   8.6   0.3 *    4303
0.73    25   20    1329   27.9   0.24 *  31.5  12.4  19.1    9.0   1.1   8.6   0.4 *    4311
0.73    25   24     729   42.4   0.38 *  31.6  12.4  19.2    9.0   1.1   8.8   0.3 *    4318
0.73    25   26     560   50.9   0.47 *  31.8  12.4  19.4    9.0   1.1   9.0   0.2 *    4348
0.73    25   18    1880   21.9   0.20 *  31.8  12.4  19.4    9.0   1.1   8.8   0.5 *    4355
0.73    25   28     439   60.3   0.57 *  32.1  12.4  19.7    9.0   1.1   9.4   0.2 *    4389
0.73    25   30     350   70.7   0.70 *  32.4  12.4  20.0    9.0   1.1   9.7   0.2 *    4438
0.73    25   16    2770   16.7   0.16 *  32.6  12.4  20.2    9.0   1.1   9.3   0.7 *    4455
0.73    25   14    4299   12.3   0.13 *  34.0  12.4  21.6    9.0   1.1  10.4   1.1 *    4652
0.73    25   12    7138    8.7   0.11 *  36.8  12.4  24.4    9.0   1.1  12.5   1.7 *    5032

                                BETA INDEXES = 100 PERCENT OF PREDICTED VALUES
0.73    25   24     973   31.8   0.30 *  32.3  12.4  19.9    9.0   1.1   9.4   0.4 *    4417
0.73    25   22    1295   26.0   0.25 *  32.3  12.4  19.9    9.0   1.1   9.3   0.5 *    4425
0.73    25   26     747   38.2   0.37 *  32.4  12.4  20.0    9.0   1.1   9.5   0.3 *    4430
0.73    25   28     586   45.2   0.45 *  32.6  12.4  20.2    9.0   1.1   9.8   0.3 *    4458
0.73    25   20    1772   20.9   0.20 *  32.6  12.4  20.2    9.0   1.1   9.5   0.6 *    4463
0.73    25   30     467   53.0   0.54 *  32.9  12.4  20.5    9.0   1.1  10.1   0.2 *    4497
0.73    25   18    2507   16.5   0.17 *  33.3  12.4  20.9    9.0   1.1  10.0   0.8 *    4551
0.73    25   16    3694   12.6   0.14 *  34.5  12.4  22.1    9.0   1.1  10.9   1.1 *    4716
0.73    25   14    5732    9.3   0.12 *  36.7  12.4  24.3    9.0   1.1  12.5   1.6 *    5017
0.73    25   12    9518    6.5   0.10 *  40.8  12.4  28.4    9.0   1.1  15.6   2.7 *    5577

                                BETA INDEXES = 125 PERCENT OF PREDICTED VALUES
0.73    25   26     934   30.5   0.31 *  33.0  12.4  20.6    9.0   1.1  10.1   0.4 *    4513
0.73    25   24    1216   25.4   0.26 *  33.0  12.4  20.6    9.0   1.1  10.0   0.5 *    4517
0.73    25   28     732   36.2   0.38 *  33.1  12.4  20.7    9.0   1.1  10.2   0.3 *    4528
0.73    25   22    1619   20.8   0.21 *  33.2  12.4  20.8    9.0   1.1  10.1   0.6 *    4548
0.73    25   30     583   42.4   0.45 *  33.3  12.4  20.9    9.0   1.1  10.5   0.3 *    4557
0.73    25   20    2216   16.8   0.18 *  33.8  12.4  21.3    9.0   1.1  10.4   0.8 *    4618
0.73    25   18    3134   13.2   0.15 *  34.7  12.4  22.3    9.0   1.1  11.2   1.0 *    4750
0.73    25   16    4617   10.0   0.13 *  36.4  12.4  24.0    9.0   1.1  12.4   1.5 *    4983
0.73    25   14    7165    7.4   0.11 *  39.4  12.4  27.0    9.0   1.1  14.7   2.2 *    5394
0.73    25   12   11897    5.2   0.10 *  45.0  12.4  32.6    9.0   1.1  18.6   3.8 *    6151

                                BETA INDEXES = 150 PERCENT OF PREDICTED VALUES
0.73    25   26    1121   25.5   0.27 *  33.6  12.4  21.2    9.0   1.1  10.6   0.5 *    4597
0.73    25   28     879   30.2   0.33 *  33.6  12.4  21.2    9.0   1.1  10.7   0.4 *    4599
0.73    25   30     700   35.3   0.39 *  33.8  12.4  21.3    9.0   1.1  10.9   0.4 *    4617
0.73    25   24    1459   21.2   0.23 *  33.8  12.4  21.4    9.0   1.1  10.6   0.6 *    4618
0.73    25   22    1943   17.4   0.19 *  34.2  12.4  21.7    9.0   1.1  10.9   0.8 *    4672
0.73    25   20    2659   14.0   0.16 *  34.9  12.4  22.5    9.0   1.1  11.4   1.0 *    4775
0.73    25   18    3761   11.0   0.14 *  36.2  12.4  23.8    9.0   1.1  12.4   1.3 *    4954
0.73    25   16    5541    8.4   0.12 *  38.4  12.4  26.0    9.0   1.1  14.0   1.9 *    5258
0.73    25   14    8598    6.2   0.11 *  42.3  12.4  29.9    9.0   1.1  16.8   3.0 *    5786
0.73    25   12   14277    4.3   0.10 *  49.4  12.4  37.0    9.0   1.1  21.6   5.2 *    6755

                                BETA INDEXES = 175 PERCENT OF PREDICTED VALUES
0.73    25   28    1025   25.9   0.29 *  34.1  12.4  21.7    9.0   1.1  11.1   0.5 *    4670
0.73    25   30     817   30.3   0.35 *  34.2  12.4  21.8    9.0   1.1  11.2   0.4 *    4678
0.73    25   26    1308   21.8   0.25 *  34.2  12.4  21.8    9.0   1.1  11.1   0.6 *    4682
0.73    25   24    1702   18.2   0.21 *  34.5  12.4  22.1    9.0   1.1  11.2   0.7 *    4721
0.73    25   22    2267   14.9   0.18 *  35.1  12.4  22.7    9.0   1.1  11.6   0.9 *    4798
0.73    25   20    3102   12.0   0.15 *  36.1  12.4  23.7    9.0   1.1  12.3   1.2 *    4935
0.73    25   18    4387    9.4   0.13 *  37.7  12.4  25.3    9.0   1.1  13.6   1.7 *    5162
0.73    25   16    6464    7.2   0.11 *  40.5  12.4  28.1    9.0   1.1  15.6   2.4 *    5541
0.73    25   14   10031    5.3   0.10 *  45.3  12.4  32.9    9.0   1.1  18.9   3.8 *    6192
0.73    25   12   16657    3.7   0.09 *  54.0  12.4  41.6    9.0   1.1  24.7   6.8 *    7390
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                    JOB 10.  SAME AS JOB 9 WITH CHANGES BELOW

                  7 XI INDEX                      5E9     FT/LB
                 12 BETA PREDICTION        3.23/0.914/-1.25/0.637
                 16 DIATOMITE COST                50     $/TON
                 20 BACKWASH COST               7, 30     GAL/SF, MIN
                   BEGIN
              ________________________________________________

FLOW  TERM   CD   B E T A   TIME   THICK * ----- COSTS, $ PER MILLION GALLONS ------ *   TOTAL
      HEAD          4  -2                 *                     LAB+                  *    COST
GSFM   FT    PPM  10 FT      HR       IN  * TOTAL   1ST  OPER  MAIN  POWR  DIAT  BAKW *    $/MO
------------------------------------------*-------------------------------------------*--------

                      BETA INDEXES =  50 PERCENT OF PREDICTED VALUES
0.73   25    18    1738     23.6    0.20 *  29.2  12.4  16.7   9.0   1.1   6.2   0.4 *    3987
0.73   25    16    2243     20.5    0.18 *  29.2  12.4  16.7   9.0   1.1   6.1   0.5 *    3988
0.73   25    20    1384     26.6    0.24 *  29.2  12.4  16.8   9.0   1.1   6.3   0.4 *    3999
0.73   25    14    2995     17.6    0.15 *  29.3  12.4  16.9   9.0   1.1   6.2   0.6 *    4007
0.73   25    22    1126     29.8    0.27 *  29.4  12.4  17.0   9.0   1.1   6.5   0.4 *    4020
0.73   25    24     933     32.9    0.31 *  29.6  12.4  17.2   9.0   1.1   6.7   0.3 *    4048
0.73   25    12    4181     14.7    0.13 *  29.7  12.4  17.2   9.0   1.1   6.4   0.7 *    4056
0.73   25    26     784     36.1    0.35 *  29.8  12.4  17.4   9.0   1.1   7.0   0.3 *    4080
0.73   25    28     668     39.4    0.40 *  30.1  12.4  17.7   9.0   1.1   7.3   0.3 *    4117
0.73   25    10    6204     11.9    0.11 *  30.4  12.4  18.0   9.0   1.1   6.9   0.9 *    4154

                      BETA INDEXES =  75 PERCENT OF PREDICTED VALUES
0.73   25    20    2076     17.8    0.18 *  30.6  12.4  18.1   9.0   1.1   7.4   0.6 *    4180
0.73   25    22    1689     19.8    0.21 *  30.6  12.4  18.2   9.0   1.1   7.5   0.6 *    4181
0.73   25    18    2608     15.7    0.16 *  30.6  12.4  18.2   9.0   1.1   7.4   0.7 *    4192
0.73   25    24    1399     21.9    0.23 *  30.7  12.4  18.2   9.0   1.1   7.6   0.5 *    4193
0.73   25    26    1177     24.1    0.26 *  30.8  12.4  18.4   9.0   1.1   7.8   0.5 *    4213
0.73   25    16    3365     13.7    0.14 *  30.9  12.4  18.5   9.0   1.1   7.5   0.8 *    4224
0.73   25    28    1002     26.3    0.29 *  31.0  12.4  18.6   9.0   1.1   8.0   0.4 *    4238
0.73   25    30     863     28.5    0.33 *  31.2  12.4  18.8   9.0   1.1   8.3   0.4 *    4268
0.73   25    14    4493     11.7    0.13 *  31.3  12.4  18.9   9.0   1.1   7.8   1.0 *    4286
0.73   25    12    6272      9.8    0.11 *  32.1  12.4  19.7   9.0   1.1   8.3   1.3 *    4394

                      BETA INDEXES = 100 PERCENT OF PREDICTED VALUES
0.73   25    24    1866     16.5    0.20 *  31.7  12.4  19.3   9.0   1.1   8.5   0.7 *    4341
0.73   25    22    2252     14.9    0.18 *  31.8  12.4  19.4   9.0   1.1   8.4   0.8 *    4346
0.73   25    26    1569     18.1    0.22 *  31.8  12.4  19.4   9.0   1.1   8.6   0.7 *    4347
0.73   25    28    1336     19.7    0.24 *  31.9  12.4  19.5   9.0   1.1   8.7   0.6 *    4362
0.73   25    20    2768     13.3    0.16 *  31.9  12.4  19.5   9.0   1.1   8.5   0.9 *    4365
0.73   25    30    1151     21.3    0.27 *  32.0  12.4  19.6   9.0   1.1   8.9   0.6 *    4382
0.73   25    18    3477     11.8    0.14 *  32.2  12.4  19.8   9.0   1.1   8.6   1.1 *    4403
0.73   25    16    4487     10.3    0.13 *  32.7  12.4  20.3   9.0   1.1   8.9   1.2 *    4469
0.73   25    14    5991      8.8    0.12 *  33.5  12.4  21.0   9.0   1.1   9.4   1.5 *    4576
0.73   25    12    8363      7.3    0.11 *  34.7  12.4  22.3   9.0   1.1  10.3   1.9 *    4749

                      BETA INDEXES = 125 PERCENT OF PREDICTED VALUES
0.73   25    26    1961     14.5    0.19 *  32.8  12.4  20.4   9.0   1.1   9.4   0.9 *    4485
0.73   25    28    1671     15.8    0.21 *  32.8  12.4  20.4   9.0   1.1   9.5   0.8 *    4487
0.73   25    24    2332     13.2    0.17 *  32.8  12.4  20.4   9.0   1.1   9.3   1.0 *    4493
0.73   25    30    1439     17.1    0.23 *  32.9  12.4  20.5   9.0   1.1   9.6   0.8 *    4498
0.73   25    22    2816     11.9    0.16 *  33.0  12.4  20.6   9.0   1.1   9.4   1.1 *    4514
0.73   25    20    3461     10.7    0.14 *  33.3  12.4  20.9   9.0   1.1   9.5   1.2 *    4554
0.73   25    18    4347      9.4    0.13 *  33.8  12.4  21.4   9.0   1.1   9.8   1.4 *    4620
0.73   25    16    5609      8.2    0.12 *  34.5  12.4  22.1   9.0   1.1  10.3   1.7 *    4721
0.73   25    14    7488      7.0    0.11 *  35.7  12.4  23.2   9.0   1.1  11.0   2.1 *    4877
0.73   25    12   10454      5.9    0.10 *  37.4  12.4  25.0   9.0   1.1  12.2   2.7 *    5120

                      BETA INDEXES = 150 PERCENT OF PREDICTED VALUES
0.73   25    28    2005     13.1    0.19 *  33.7  12.4  21.3   9.0   1.1  10.2   1.0 *    4615
0.73   25    30    1727     14.2    0.20 *  33.7  12.4  21.3   9.0   1.1  10.3   0.9 *    4615
0.73   25    26    2354     12.0    0.17 *  33.8  12.4  21.4   9.0   1.1  10.2   1.1 *    4625
0.73   25    24    2799     11.0    0.16 *  34.0  12.4  21.6   9.0   1.1  10.2   1.2 *    4647
0.73   25    22    3379      9.9    0.14 *  34.3  12.4  21.9   9.0   1.1  10.3   1.4 *    4687
0.73   25    20    4153      8.9    0.13 *  34.7  12.4  22.3   9.0   1.1  10.6   1.6 *    4749
0.73   25    18    5216      7.9    0.12 *  35.4  12.4  23.0   9.0   1.1  11.0   1.9 *    4843
0.73   25    16    6731      6.8    0.11 *  36.4  12.4  24.0   9.0   1.1  11.7   2.2 *    4982
0.73   25    14    8986      5.9    0.10 *  37.9  12.4  25.5   9.0   1.1  12.7   2.8 *    5190
0.73   25    12   12545      4.9    0.10 *  40.3  12.4  27.9   9.0   1.1  14.2   3.6 *    5510

                      BETA INDEXES = 175 PERCENT OF PREDICTED VALUES
0.73   25    30    2015     12.2    0.19 *  34.6  12.4  22.2   9.0   1.1  10.9   1.2 *    4735
0.73   25    28    2339     11.3    0.17 *  34.7  12.4  22.3   9.0   1.1  10.9   1.3 *    4745
0.73   25    26    2746     10.3    0.16 *  34.9  12.4  22.4   9.0   1.1  10.9   1.4 *    4767
0.73   25    24    3265      9.4    0.15 *  35.1  12.4  22.7   9.0   1.1  11.1   1.5 *    4805
0.73   25    22    3942      8.5    0.13 *  35.6  12.4  23.1   9.0   1.1  11.3   1.7 *    4863
0.73   25    20    4845      7.6    0.12 *  36.2  12.4  23.8   9.0   1.1  11.7   2.0 *    4949
0.73   25    18    6086      6.7    0.12 *  37.1  12.4  24.7   9.0   1.1  12.2   2.3 *    5072
0.73   25    16    7853      5.9    0.11 *  38.4  12.4  26.0   9.0   1.1  13.1   2.8 *    5252
0.73   25    14   10484      5.0    0.10 *  40.3  12.4  27.9   9.0   1.1  14.3   3.5 *    5516
0.73   25    12   14635      4.2    0.09 *  43.3  12.4  30.9   9.0   1.1  16.1   4.6 *    5918
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                    JOB 11.  SAME AS JOB 10 WITH FOLLOWING CHANGES

                  1 DESIGN FLOW              7     MGD
                 13 UNIT FLOW RATE        0.5/0.25/3.5          GSFM
                 14 BODY FEED             10/5/50               PPM
                 20 BACKWASH COST           10, 30   GAL/SF, MIN
                   BEGIN
               ______________________________________________________________

FLOW   TERM    CD  B E T A  TIME   THICK * ----- COSTS, $ PER MILLION GALLONS ------ *   TOTAL
       HEAD          4  -2                *                    LAB+                   *    COST
GSFM    FT    PPM  10 FT     HR       IN  * TOTAL    1ST  OPER  MAIN  POWR  DIAT  BAKW *    $/MO
------------------------------------------*-----------------------------------------------*--------

                                   BETA INDEXES =  50 PERCENT OF PREDICTED VALUES
1.75     25    30     575    7.3   0.23 *  23.4    6.4  17.0   5.1   1.1   9.5   1.3 *    4988
1.75     25    25     854    5.9   0.18 *  23.5    6.4  17.1   5.1   1.1   9.2   1.6 *    4996
1.50     25    25     854    8.1   0.20 *  23.5    7.1  16.4   5.5   1.1   8.6   1.2 *    5003
2.00     25    30     575    5.6   0.21 *  23.5    5.9  17.7   4.8   1.1  10.0   1.7 *    5011
1.50     25    30     575   10.0   0.26 *  23.7    7.1  16.6   5.5   1.1   9.0   1.0 *    5040
2.00     25    35     412    6.7   0.27 *  23.7    5.9  17.8   4.8   1.1  10.4   1.5 *    5045
1.75     25    35     412    8.7   0.29 *  23.8    6.4  17.4   5.1   1.1  10.0   1.1 *    5055
2.00     25    25     854    4.5   0.17 *  23.8    5.9  17.9   4.8   1.1   9.8   2.2 *    5070
1.50     25    20    1384    6.2   0.15 *  23.9    7.1  16.8   5.5   1.1   8.6   1.5 *    5079
2.25     25    35     412    5.2   0.25 *  23.9    5.5  18.4   4.6   1.1  10.8   1.9 *    5088

                                   BETA INDEXES =  75 PERCENT OF PREDICTED VALUES
1.50     25    30     863    6.7   0.20 *  25.7    7.1  18.6   5.5   1.1  10.4   1.6 *    5476
1.50     25    35     618    8.0   0.25 *  25.8    7.1  18.7   5.5   1.1  10.8   1.4 *    5498
1.75     25    35     618    5.8   0.22 *  25.9    6.4  19.5   5.1   1.1  11.4   1.9 *    5508
1.25     25    30     863    9.6   0.22 *  26.0    8.1  17.9   6.0   1.1   9.7   1.1 *    5535
1.75     25    30     863    4.9   0.18 *  26.0    6.4  19.6   5.1   1.1  11.1   2.3 *    5537
1.25     25    25    1281    7.8   0.18 *  26.1    8.1  18.0   6.0   1.1   9.5   1.4 *    5544
1.75     25    40     463    6.8   0.27 *  26.1    6.4  19.7   5.1   1.1  11.8   1.6 *    5551
1.50     25    25    1281    5.4   0.16 *  26.1    7.1  19.0   5.5   1.1  10.4   2.0 *    5553
1.50     25    40     463    9.3   0.30 *  26.2    7.1  19.1   5.5   1.1  11.3   1.2 *    5576
1.25     25    35     618   11.5   0.28 *  26.3    8.1  18.2   6.0   1.1  10.2   1.0 *    5600

                                   BETA INDEXES = 100 PERCENT OF PREDICTED VALUES
1.50     25    35     824    6.0   0.21 *  27.6    7.1  20.5   5.5   1.1  11.9   2.0 *    5879
1.25     25    30    1151    7.2   0.19 *  27.7    8.1  19.6   6.0   1.1  10.9   1.6 *    5890
1.25     25    35     824    8.6   0.23 *  27.7    8.1  19.6   6.0   1.1  11.1   1.4 *    5894
1.50     25    40     617    7.0   0.25 *  27.7    7.1  20.6   5.5   1.1  12.3   1.7 *    5900
1.50     25    30    1151    5.0   0.17 *  27.9    7.1  20.8   5.5   1.1  11.8   2.4 *    5941
1.25     25    40     617   10.1   0.28 *  28.0    8.1  19.9   6.0   1.1  11.6   1.2 *    5959
1.75     25    40     617    5.1   0.22 *  28.0    6.4  21.6   5.1   1.1  13.0   2.4 *    5960
1.50     25    45     478    8.0   0.30 *  28.1    7.1  21.0   5.5   1.1  12.8   1.5 *    5972
1.25     25    25    1708    5.8   0.15 *  28.2    8.1  20.1   6.0   1.1  10.9   2.1 *    5992
1.75     25    35     824    4.4   0.19 *  28.2    6.4  21.8   5.1   1.1  12.7   2.8 *    5993

                                   BETA INDEXES = 125 PERCENT OF PREDICTED VALUES
1.25     25    35    1031    6.9   0.20 *  29.1    8.1  21.1   6.0   1.1  12.1   1.8 *    6199
1.25     25    40     772    8.1   0.24 *  29.2    8.1  21.1   6.0   1.1  12.5   1.6 *    6218
1.50     25    40     772    5.6   0.21 *  29.3    7.1  22.2   5.5   1.1  13.3   2.3 *    6238
1.25     25    30    1439    5.8   0.17 *  29.4    8.1  21.3   6.0   1.1  12.0   2.2 *    6261
1.50     25    45     598    6.4   0.25 *  29.4    7.1  22.3   5.5   1.1  13.7   2.0 *    6264
1.50     25    35    1031    4.8   0.18 *  29.5    7.1  22.4   5.5   1.1  13.1   2.7 *    6280
1.25     25    45     598    9.3   0.29 *  29.6    8.1  21.5   6.0   1.1  13.0   1.4 *    6289
1.00     25    30    1439    9.1   0.19 *  29.7    9.5  20.1   6.8   1.1  10.8   1.4 *    6316
1.00     25    35    1031   10.8   0.23 *  29.7    9.5  20.2   6.8   1.1  11.1   1.2 *    6328
1.50     25    50     476    7.2   0.30 *  29.8    7.1  22.7   5.5   1.1  14.2   1.8 *    6336

                                   BETA INDEXES = 150 PERCENT OF PREDICTED VALUES
1.25     25    40     926    6.7   0.21 *  30.5    8.1  22.4   6.0   1.1  13.3   2.0 *    6485
1.25     25    35    1237    5.8   0.18 *  30.6    8.1  22.5   6.0   1.1  13.1   2.4 *    6515
1.25     25    45     718    7.7   0.25 *  30.6    8.1  22.6   6.0   1.1  13.7   1.8 *    6521
1.00     25    35    1237    9.0   0.21 *  30.8    9.5  21.3   6.8   1.1  11.9   1.5 *    6559
1.50     25    45     718    5.3   0.22 *  30.9    7.1  23.8   5.5   1.1  14.6   2.6 *    6568
1.50     25    40     926    4.7   0.19 *  31.0    7.1  23.9   5.5   1.1  14.3   3.0 *    6591
1.00     25    30    1727    7.6   0.17 *  31.0    9.5  21.5   6.8   1.1  11.8   1.8 *    6595
1.00     25    40     926   10.6   0.25 *  31.0    9.5  21.5   6.8   1.1  12.3   1.3 *    6596
1.25     25    50     571    8.7   0.30 *  31.0    8.1  22.9   6.0   1.1  14.2   1.6 *    6599
1.50     25    50     571    6.0   0.26 *  31.0    7.1  23.9   5.5   1.1  15.0   2.3 *    6603

                                   BETA INDEXES = 175 PERCENT OF PREDICTED VALUES
1.25     25    45     837    6.6   0.23 *  31.8    8.1  23.7   6.0   1.1  14.4   2.2 *    6758
1.25     25    40    1081    5.8   0.20 *  31.8    8.1  23.7   6.0   1.1  14.1   2.5 *    6761
1.00     25    35    1443    7.7   0.19 *  31.9    9.5  22.4   6.8   1.1  12.7   1.8 *    6795
1.00     25    40    1081    9.0   0.22 *  31.9    9.5  22.4   6.8   1.1  12.9   1.6 *    6796
1.25     25    50     667    7.5   0.27 *  32.0    8.1  23.9   6.0   1.1  14.9   1.9 *    6808
1.25     25    35    1443    4.9   0.17 *  32.2    8.1  24.1   6.0   1.1  14.0   2.9 *    6844
1.00     25    45     837   10.4   0.27 *  32.2    9.5  22.7   6.8   1.1  13.4   1.4 *    6853
1.50     25    50     667    5.2   0.24 *  32.3    7.1  25.2   5.5   1.1  15.8   2.8 *    6879
1.00     25    30    2015    6.5   0.16 *  32.4    9.5  22.8   6.8   1.1  12.7   2.2 *    6884
1.50     25    45     837    4.6   0.20 *  32.4    7.1  25.2   5.5   1.1  15.4   3.2 *    6864
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                    JOB 12.  SAME AS JOB 11 WITH FOLLOWING CHANGES

                  11 SEPTUM DIAMETER              1    INCHES
                  15 TERMINAL HEAD             25/10/150        FT
                    BEGIN
               ____________________________________________________

FLOW  TERM   CD  B E T A  TIME  THICK * ----- COSTS, $ PER MILLION GALLONS ------ *  TOTAL
      HEAD          4  -2               *                       LAB+                 *   COST
GSFM   FT   PPM  10 FT     HR     IN    * TOTAL   1ST  OPER  MAIN  POWR  DIAT  BAKW *   $/MO
----------------------------------------*--------------------------------------------*--------

                            BETA INDEXES =  50 PERCENT OF PREDICTED VALUES
2.75   75   20    1384    9.8   0.24 *  18.9    4.9  14.0   4.3   3.4   5.7   0.6 *    4031
2.50   65   20    1384   10.1   0.23 *  18.9    5.2  13.8   4.4   2.9   5.8   0.6 *    4032
2.75   65   20    1384    8.1   0.22 *  19.0    4.9  14.1   4.3   2.9   6.0   0.8 *    4033
3.00   75   20    1384    8.0   0.23 *  19.0    4.7  14.3   4.2   3.4   5.9   0.8 *    4036
2.50   75   20    1384   12.2   0.26 *  19.0    5.2  13.8   4.4   3.4   5.5   0.5 *    4042
3.00   85   20    1384    9.4   0.25 *  19.0    4.7  14.3   4.2   3.8   5.6   0.6 *    4049
3.00   65   20    1384    6.7   0.21 *  19.0    4.7  14.4   4.2   2.9   6.2   1.0 *    4053
2.75   85   20    1384   11.5   0.27 *  19.0    4.9  14.1   4.3   3.8   5.5   0.5 *    4053
2.50   55   20    1384    8.2   0.21 *  19.1    5.2  13.9   4.4   2.5   6.2   0.8 *    4056
3.25   75   20    1384    6.7   0.21 *  19.1    4.5  14.5   4.2   3.4   6.1   0.9 *    4057

                            BETA INDEXES =  75 PERCENT OF PREDICTED VALUES
2.50   85   20    2076    8.6   0.21 *  20.3    5.2  15.1   4.4   3.8   6.1   0.8 *    4318
2.50   75   20    2076    7.4   0.20 *  20.3    5.2  15.2   4.4   3.4   6.4   0.9 *    4324
2.25   75   20    2076    9.3   0.21 *  20.3    5.5  14.9   4.6   3.4   6.2   0.7 *    4327
2.50   75   25    1281   10.8   0.28 *  20.4    5.2  15.2   4.4   3.4   6.8   0.6 *    4331
2.75   75   25    1281    8.6   0.26 *  20.4    4.9  15.5   4.3   3.4   7.0   0.8 *    4333
2.75   85   20    2076    6.9   0.20 *  20.4    4.9  15.5   4.3   3.8   6.4   1.0 *    4333
2.50   95   20    2076    9.8   0.23 *  20.4    5.2  15.2   4.4   4.3   5.9   0.7 *    4334
2.25   85   20    2076   10.9   0.23 *  20.4    5.5  14.9   4.6   3.8   5.9   0.6 *    4335
2.50   65   25    1281    8.9   0.25 *  20.4    5.2  15.2   4.4   2.9   7.1   0.8 *    4337
2.75   95   20    2076    7.9   0.22 *  20.4    4.9  15.5   4.3   4.3   6.1   0.8 *    4338

                            BETA INDEXES = 100 PERCENT OF PREDICTED VALUES
2.50   85   25    1708    8.7   0.25 *  21.3    5.2  16.2   4.4   3.8   7.1   0.8 *    4542
2.25   75   25    1708    9.5   0.24 *  21.4    5.5  15.9   4.6   3.4   7.2   0.8 *    4552
2.50   75   25    1708    7.5   0.22 *  21.4    5.2  16.3   4.4   3.4   7.4   1.0 *    4554
2.50   95   25    1708   10.1   0.27 *  21.4    5.2  16.3   4.4   4.3   6.9   0.7 *    4555
2.25   85   25    1708   11.1   0.27 *  21.4    5.5  15.9   4.6   3.8   6.9   0.6 *    4556
2.25   85   20    2768    7.7   0.19 *  21.4    5.5  15.9   4.6   3.8   6.6   0.9 *    4557
2.25   95   20    2768    8.8   0.20 *  21.4    5.5  15.9   4.6   4.3   6.3   0.8 *    4558
2.50   95   20    2768    6.9   0.19 *  21.4    5.2  16.3   4.4   4.3   6.6   1.0 *    4561
2.75   95   25    1708    8.1   0.25 *  21.4    4.9  16.5   4.3   4.3   7.1   0.9 *    4563
2.75   85   25    1708    7.0   0.23 *  21.4    4.9  16.5   4.3   3.8   7.4   1.0 *    4563

                            BETA INDEXES = 125 PERCENT OF PREDICTED VALUES
2.25   85   25    2135    8.4   0.22 *  22.2    5.5  16.8   4.6   3.8   7.4   0.9 *    4728
2.25   95   25    2135    9.7   0.24 *  22.2    5.5  16.8   4.6   4.3   7.1   0.8 *    4732
2.50   95   25    2135    7.6   0.23 *  22.2    5.2  17.1   4.4   4.3   7.4   1.0 *    4732
2.50  105   25    2135    8.6   0.24 *  22.3    5.2  17.1   4.4   4.7   7.1   0.8 *    4742
2.50   85   25    2135    6.6   0.21 *  22.3    5.2  17.1   4.4   3.8   7.7   1.2 *    4745
2.00   85   25    2135   11.0   0.25 *  22.3    5.9  16.4   4.8   3.8   7.1   0.7 *    4751
2.25   75   25    2135    7.2   0.21 *  22.3    5.5  16.9   4.6   3.4   7.8   1.1 *    4752
2.50   85   30    1439    9.1   0.28 *  22.3    5.2  17.2   4.4   3.8   8.1   0.9 *    4754
2.25  105   25    2135   11.0   0.26 *  22.3    5.5  16.9   4.6   4.7   6.9   0.7 *    4755
2.00   75   25    2135    9.4   0.22 *  22.4    5.9  16.5   4.8   3.4   7.4   0.8 *    4756

                            BETA INDEXES = 150 PERCENT OF PREDICTED VALUES
2.25   95   25    2562    7.7   0.21 *  23.0    5.5  17.5   4.6   4.3   7.6   1.0 *    4889
2.25  105   25    2562    8.7   0.23 *  23.0    5.5  17.5   4.6   4.7   7.3   0.9 *    4894
2.00   95   25    2562   10.0   0.23 *  23.0    5.9  17.2   4.8   4.3   7.3   0.8 *    4902
2.00   85   25    2562    8.7   0.21 *  23.0    5.9  17.2   4.8   3.8   7.6   0.9 *    4902
2.25   85   30    1727    9.2   0.26 *  23.1    5.5  17.6   4.6   3.8   8.3   0.9 *    4906
2.50  105   25    2562    6.9   0.21 *  23.1    5.2  17.9   4.4   4.7   7.6   1.1 *    4906
2.25   85   25    2562    6.7   0.20 *  23.1    5.5  17.6   4.6   3.8   8.0   1.2 *    4908
2.50   95   30    1727    8.3   0.27 *  23.1    5.2  17.9   4.4   4.3   8.3   1.0 *    4909
2.25   95   30    1727   10.6   0.29 *  23.1    5.5  17.6   4.6   4.3   8.0   0.8 *    4912
2.50  115   25    2562    7.7   0.23 *  23.1    5.2  18.0   4.4   5.2   7.4   1.0 *    4916

                            BETA INDEXES = 175 PERCENT OF PREDICTED VALUES
2.00   95   25    2989    8.3   0.21 *  23.7    5.9  17.8   4.8   4.3   7.7   1.0 *    5038
2.25  105   25    2989    7.2   0.21 *  23.7    5.5  18.2   4.6   4.7   7.8   1.1 *    5039
2.25   95   30    2015    8.7   0.26 *  23.7    5.5  18.2   4.6   4.3   8.4   1.0 *    5039
2.00  105   25    2989    9.4   0.22 *  23.7    5.9  17.8   4.8   4.7   7.4   0.9 *    5043
2.25  115   25    2989    8.1   0.22 *  23.7    5.5  18.2   4.6   5.2   7.5   1.0 *    5046
2.25  105   30    2015    9.9   0.28 *  23.7    5.5  18.3   4.6   4.7   8.1   0.8 *    5049
2.25   85   30    2015    7.5   0.23 *  23.7    5.5  18.3   4.6   3.8   8.7   1.1 *    5052
2.25   95   25    2989    6.4   0.19 *  23.7    5.5  18.3   4.6   4.3   8.1   1.3 *    5052
2.00   85   30    2015    9.8   0.26 *  23.8    5.9  17.9   4.8   3.8   8.4   0.9 *    5054
2.50  105   30    2015    7.7   0.25 *  23.8    5.2  18.6   4.4   4.7   8.4   1.1 *    5054
```

```
              JOB 13.  SAME AS JOB 12 EXCEPT 25 MGD

           1 DESIGN FLOW              25    MGD
            BEGIN

FLOW  TERM   CD  B E T A  TIME   THICK * ----- COSTS, $ PER MILLION GALLONS ------ *   TOTAL
      HEAD          4  -2                *                    LAB+                  *    COST
GSFM   FT   PPM  10 FT     HR       IN   * TOTAL   1ST  OPER  MAIN  POWR  DIAT  BAKW *    $/MO
-----------------------------------------*------------------------------------------*--------

                    BETA INDEXES =  50 PERCENT OF PREDICTED VALUES
3.00    75   20     1384    8.0   0.23 *  17.4    4.4  13.0   3.1   3.4   5.9   0.7 *   13254
2.75    65   20     1384    8.1   0.22 *  17.5    4.6  12.8   3.2   2.9   6.0   0.7 *   13263
2.75    75   20     1384    9.8   0.24 *  17.5    4.6  12.8   3.2   3.4   5.7   0.6 *   13265
2.50    65   20     1384   10.1   0.23 *  17.5    4.9  12.6   3.3   2.9   5.8   0.6 *   13293
3.25    75   20     1384    6.7   0.21 *  17.5    4.2  13.3   3.0   3.4   6.1   0.8 *   13295
3.00    65   20     1384    6.7   0.21 *  17.5    4.4  13.1   3.1   2.9   6.2   0.9 *   13300
3.00    85   20     1384    9.4   0.25 *  17.5    4.4  13.1   3.1   3.8   5.6   0.6 *   13308
3.25    85   20     1384    7.8   0.24 *  17.5    4.2  13.3   3.0   3.8   5.8   0.7 *   13311
2.50    75   20     1384   12.2   0.26 *  17.6    4.9  12.7   3.3   3.4   5.5   0.5 *   13339
2.75    85   20     1384   11.5   0.27 *  17.6    4.6  12.9   3.2   3.8   5.5   0.5 *   13354

                    BETA INDEXES =  75 PERCENT OF PREDICTED VALUES
2.50    85   20     2076    8.6   0.21 *  18.8    4.9  13.9   3.3   3.8   6.1   0.7 *   14303
2.50    75   20     2076    7.4   0.20 *  18.8    4.9  14.0   3.3   3.4   6.4   0.8 *   14317
2.75    85   20     2076    6.9   0.20 *  18.8    4.6  14.2   3.2   3.8   6.4   0.9 *   14322
2.25    75   20     2076    9.3   0.21 *  18.9    5.2  13.7   3.5   3.4   6.2   0.7 *   14332
2.75    75   25     1281    8.6   0.26 *  18.9    4.6  14.2   3.2   3.4   7.0   0.7 *   14338
2.75    95   20     2076    7.9   0.22 *  18.9    4.6  14.2   3.2   4.3   6.1   0.7 *   14348
2.50    75   25     1281   10.8   0.28 *  13.9    4.9  14.0   3.3   3.4   6.8   0.6 *   14363
2.25    85   20     2076   10.9   0.23 *  18.9    5.2  13.7   3.5   3.8   5.9   0.5 *   14369
2.50    95   20     2076    9.8   0.23 *  18.9    4.9  14.0   3.3   4.3   5.9   0.6 *   14371
3.00    85   25     1281    8.3   0.27 *  18.9    4.4  14.5   3.1   3.8   6.9   0.7 *   14376

                    BETA INDEXES = 100 PERCENT OF PREDICTED VALUES
2.50    85   25     1708    8.7   0.25 *  19.9    4.9  15.0   3.3   3.8   7.1   0.8 *   15107
2.25    75   25     1708    9.5   0.24 *  19.9    5.2  14.7   3.5   3.4   7.2   0.7 *   15135
2.50    75   25     1708    7.5   0.22 *  19.9    4.9  15.0   3.3   3.4   7.4   0.9 *   15138
2.25    85   20     2768    7.7   0.19 *  19.9    5.2  14.7   3.5   3.8   6.6   0.9 *   15140
2.75    85   25     1708    7.0   0.23 *  19.9    4.6  15.3   3.2   3.8   7.4   0.9 *   15144
2.25    95   20     2768    8.8   0.20 *  19.9    5.2  14.7   3.5   4.3   6.3   0.7 *   15152
2.75    95   25     1708    8.1   0.25 *  19.9    4.6  15.3   3.2   4.3   7.1   0.8 *   15154
2.25    85   25     1708   11.1   0.27 *  19.9    5.2  14.7   3.5   3.8   6.9   0.6 *   15158
2.50    95   20     2768    6.9   0.19 *  19.9    4.9  15.1   3.3   4.3   6.6   0.9 *   15158
2.50    95   25     1708   10.1   0.27 *  20.0    4.9  15.1   3.3   4.3   6.9   0.6 *   15162

                    BETA INDEXES = 125 PERCENT OF PREDICTED VALUES
2.25    85   25     2135    8.4   0.22 *  20.7    5.2  15.5   3.5   3.8   7.4   0.8 *   15758
2.50    95   25     2135    7.6   0.23 *  20.8    4.9  15.9   3.3   4.3   7.4   0.9 *   15776
2.25    95   25     2135    9.7   0.24 *  20.8    5.2  15.6   3.5   4.3   7.1   0.7 *   15780
2.50    85   25     2135    6.6   0.21 *  20.8    4.9  15.9   3.3   3.8   7.7   1.1 *   15810
2.50   105   25     2135    8.6   0.24 *  20.8    4.9  15.9   3.3   4.7   7.1   0.8 *   15821
2.00    85   25     2135   11.0   0.25 *  20.8    5.6  15.2   3.7   3.8   7.1   0.6 *   15826
2.25    75   25     2135    7.2   0.21 *  20.8    5.2  15.6   3.5   3.4   7.8   1.0 *   15833
2.00    75   25     2135    9.4   0.22 *  20.8    5.6  15.2   3.7   3.4   7.4   0.8 *   15834
2.00    95   20     3461    8.7   0.19 *  20.9    5.6  15.3   3.7   4.3   6.6   0.8 *   15858
2.25    95   20     3461    6.7   0.18 *  20.9    5.2  15.7   3.5   4.3   6.9   1.0 *   15861

                    BETA INDEXES = 150 PERCENT OF PREDICTED VALUES
2.25    95   25     2562    7.7   0.21 *  21.5    5.2  16.3   3.5   4.3   7.6   0.9 *   16327
2.00    85   25     2562    8.7   0.21 *  21.5    5.6  15.9   3.7   3.8   7.6   0.8 *   16352
2.25   105   25     2562    8.7   0.23 *  21.5    5.2  16.3   3.5   4.7   7.3   0.8 *   16353
2.00    95   25     2562   10.0   0.23 *  21.5    5.6  15.9   3.7   4.3   7.3   0.7 *   16359
2.25    85   25     2562    6.7   0.20 *  21.6    5.2  16.4   3.5   3.8   8.0   1.1 *   16384
2.50   105   25     2562    6.9   0.21 *  21.6    4.9  16.7   3.3   4.7   7.6   1.0 *   16389
2.25    85   30     1727    9.2   0.26 *  21.6    5.2  16.4   3.5   3.8   8.3   0.8 *   16398
2.50    95   30     1727    8.3   0.27 *  21.6    4.9  16.7   3.3   4.3   8.3   0.9 *   16415
2.50    95   25     2562    6.1   0.20 *  21.6    4.9  16.7   3.3   4.3   7.9   1.2 *   16418
2.25    95   30     1727   10.6   0.29 *  21.6    5.2  16.4   3.5   4.3   8.0   0.7 *   16427

                    BETA INDEXES = 175 PERCENT OF PREDICTED VALUES
2.00    95   25     2989    8.3   0.21 *  22.2    5.6  16.6   3.7   4.3   7.7   0.9 *   16835
2.25   105   25     2989    7.2   0.21 *  22.2    5.2  17.0   3.5   4.7   7.8   1.0 *   16855
2.00   105   25     2989    9.4   0.22 *  22.2    5.6  16.6   3.7   4.7   7.4   0.8 *   16858
2.25    95   30     2015    8.7   0.26 *  22.2    5.2  17.0   3.5   4.3   8.4   0.9 *   16870
2.25   115   25     2989    8.1   0.22 *  22.2    5.2  17.0   3.5   5.2   7.5   0.9 *   16890
2.25    95   25     2989    6.4   0.19 *  22.2    5.2  17.0   3.5   4.3   8.1   1.2 *   16894
2.00    85   25     2989    7.2   0.19 *  22.2    5.6  16.6   3.7   3.8   8.1   1.1 *   16896
2.00    85   30     2015    9.8   0.26 *  22.2    5.6  16.6   3.7   3.8   8.4   0.8 *   16900
2.25    85   30     2015    7.5   0.23 *  22.2    5.2  17.0   3.5   3.8   8.7   1.0 *   16905
2.25   105   30     2015    9.9   0.28 *  22.3    5.2  17.1   3.5   4.7   8.1   0.7 *   16915
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FORTRAN LIST
for
POPO

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C                         FORTRAN LIST
C
C  P O P O -- PROGRAM FOR OPTIMIZATION OF PLANT OPERATION
C
      DIMENSION IN(40),B(4),ANS(13,10)
      COMMON IN,FACTR,UQ,QI,QS,QF,CD,CDI,CDS,CDF,TH,THI,THS,
     1 THF,XI,B,HP,HC,VIS,W,XLP,GP,G,PHI,RS,RO,TR,THICK,AREA,
     2 RF,SIGMA,CDE,CPO,CF,CL,CM,CB,QGPM,COPER,CTOTL,GW,AMORT,
     3 QMGMO,EFF,CS,BETA,ANS
C
C                           NOMENCLATURE
C   IN=INPUT ARRAY                      UQ=UNIT FLOW, FPH
C   FACTR=BETA MULTIPLICATION           QI,QS,QF=INITIAL,STEP,FINAL
C      FACTOR                              VALUES OF UQ, FPH
C   CD=BODY FEED CON, PPM               TH=TERMINAL HEAD LOSS, FT
C   CDI,CDS,CDF=INITIAL,STEP,           THI,THS,THF=INITIAL,STEP,
C      FINAL VALUES OF CD                  FINAL VALUES OF TH
C   XI=XI INDEX, FT/LB                  B=ARRAY CONTAINING BETA
C   HP=PRECOAT HEAD LOSS, FT               PREDICTION COEFFICIENTS
C   HC=FILTER CAKE HEAD LOSS            VIS=KINEMATIC VISCOSITY,
C   W=PRECOAT WEIGHT, LB/SF                SF/HR
C   XLP=PRECOAT THICKNESS, FT           GP=PRECOAT DENSITY, LB/CF
C   G=GRAVITY, FT/HR/HR                 PHI=PHI
C   RS=SEPTUM RADIUS, FT                RO=R SUB ZERO
C   TR=TIME OF RUN, HR                  THICK=THICKNESS OF FILTER
C   AREA=SEPTUM FILTER AREA, SF            CAKE + XLP, FT
C   RF=RATE FACTOR                      SIGMA=SIGMA
C   CDE=DIATOMITE COST, $/MO            CPO=POWER COST, $/MO
C   CF=FIRST COST, $/MO                 CL=LABOR COST, $/MO
C   CM=MAINTENANCE COST, $/MO           CB=BACKWASH COST, $/MO
C   QGPM=DESIGN FLOW, GPM               COPER=OPERATING COSTS, $/MO
C   CTOTL=TOTAL COST, $/MO              GW= DENSITY OF WATER, LB/CF
C   AMORT=AMORTIZATION FACTOR           QMGMO=DESIGN FLOW, MG/MO
C   EFF=ENERGY CONVERSION               CS=SOLIDS CONCENTRATION,PPM
C      EFFICIENCY                       ANS=ARRAY WHERE RESULTS ARE
C   BETA=BETA INDEX                        STORED UNTIL PRINTED
C
C  COSTS ARE COMPUTED FOR EVERY COMBINATION OF UQ, CD, AND TH.
C  CHEAPEST 10 COMBINATIONS ARE STORED FOR SUBSEQUENT OUTPUT.
C
C  *  SUBROUTINE READR READS IN ALL INPUT DATA
    1 CALL READR
          DO 10 MM=50,175,25
          FACTR=FLOATF(MM)/100.0
C  * * *  COSTS ARE COMPUTED FOR FACTR TIMES PREDICTED BETA
C  * * *  INDEX, WHERE FACTR = 0.50,0.75,1.00,1.25,1.50,1.75
                    UQ=QI-QS
    5               UQ=UQ+QS
C  * * * * * * * * *  STMTS BETWEEN HERE AND STMT 9 REPEATED FOR
C  * * * * * * * * *  UQ=QI,QI+QS,QI+QS+QS, ..., QF
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                    IF(UQ-QF)2,2,7
    2                         CD=CDI-CDS
    6                         CD=CD+CDS
C   *  *  *  *  *  *  *  *  * STMTS HERE TO STMNT 9 REPEATED
C   *  *  *  *  *  *  *  *  * FOR CD=CDI,CDI+CDS, ..., CDF
                              IF(CD-CDF)3,3,5
    3                                   TH=THI-THS
    8                                   TH=TH+THS
C   *   *   *   *   *   *   *   *   *   STMNTS FROM HERE TO 9
C   *   *   *   *   *   *   *   *   *   REPEATED FOR TH=THI,
C   *   *   *   *   *   *   *   *   *   THI+THS, ..., THF
                                        IF(TH-THF)4,4,6
    4                                   CALL DIEQS
                                        CALL COSTS
                                        CALL STRES
    9                                   GO TO 8
C   * * *     RESULTS ARE PRINTED FOR EACH VALUE OF FACTR
    7     CALL OUTPT
   10     CONTINUE
      GO TO 1
      END


      SUBROUTINE READR
      DIMENSION IN(40),B(4),ANS(13,10)
      COMMON IN,FACTR,UQ,QI,QS,QF,CD,CDI,CDS,CDF,TH,THI,THS,
     1 THF,XI,B,HP,HC,VIS,W,XLP,GP,G,PHI,RS,RO,TR,THICK,AREA,
     2 RF,SIGMA,CDE,CPO,CF,CL,CM,CB,QGPM,COPER,CTOTL,GW,AMORT,
     3 QMGMO,EFF,CS,BETA,ANS
C
C                  READR NOMENCLATURE
C   INDEX=CARD NUMBER, NUMBER        QMD=DESIGN FLOW, MGD
C      IN COLUMNS 1 TO 4             PCT=SALVAGE VALUE PERCENT
C   RATEI=RATE OF INTEREST           YRS=PLANT LIFE
C
C                     DATA CARD FORMATS
C    1 DESIGN FLOW                           MGD
C    2 SALVAGE VALUE                         PERCENT FIRST COST
C    3 ENERGY CONVERSION                     PERCENT
C    4 INTEREST RATE                         PERCENT
C    5 PLANT LIFE                            YEARS
C    6 SOLIDS  (CS)                          PPM
C    7 XI INDEX                              FT/LB
C    8 TEMPERATURE                           DEGREES F
C    9 PRECOAT WEIGHT                        LB/SF
C   10 PRECOAT DENSITY                       LB/CF
C   11 SEPTUM DIAMETER                       INCHES
C   12 BETA PREDICTION
C   13 UNIT FLOW RATE                                  GSFM
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C   14 BODY FEED                                                PPM
C   15 TERMINAL HEAD                                            FT
C   16 DIATOMITE COST               BRANCH TO CDIAT
C   17 FIRST COST                   BRANCH TO CFUST
C   18 POWER COST                   BRANCH TO CPOWR
C   19 LABOR COST                   BRANCH TO CLABR
C   20 BACKWASH COST                BRANCH TO CBAKW
C   21 MAINTENANCE COST             BRANCH TO CMAIN
C     BEGIN
C
      WRITE(2,31)
   31 FORMAT(46H1P O P O -- PROGRAM FOR OPTIMIZATION OF PLANT
     1  9HOPERATION/1H0)
      BIG=1000000.**8.0
C  7TH ROW OF ANS IS INITIALIZED WITH LARGE NUMBER
      DO 100 L=1,10
  100 ANS(7,L)=BIG
      G=32.2*3600.0*3600.0
      GW=62.4
C  CARDS ARE READ WITH ALPHAMERIC FORMAT AND STORED IN IN
C  ARRAY.  5TH ELEMENT OF IN CORRESPONDS TO 6TH COLUMN OF CARD
C  10TH THROUGH 34TH ELEMENTS OF IN CORRESPOND TO 26TH THROUGH
C  50TH COLUMNS OF CARD.  INDEX OR CARD NUMBER IS STORED IN
C  ELEMENTS 1 TO 4 OF IN.  OTHER INPUT NUMBERS (COLUMNS 26-50
C  OF CARD) ARE STORED IN ELEMENTS 10-34 OF IN.  CAUTION.  IF
C  INPUT CARD CONTAINS MORE THAN 1 NUMBER IN COLUMNS 26-50
C  (E.G., CARDS WITH INDEX=12,13,14, OR 15), NUMBERS MUST BE
C  SEPARATED BY BLANK CHARACTERS EXCEPT FOR 1ST CHARACTER
C  FOLLOWING NUMBER -- IT CAN BE ANY CHARACTER OTHER THAN  +
C  -  .  E   OR A DIGIT.
   45 READ(1,40)(IN(I),I=1,40)
      WRITE(2,40)(IN(I),I=1,40)
   40 FORMAT(1X5A1,A4,3A5,25A1,6A5)
C  IF COLUMN 6 CONTAINS B, BRANCH TO 41, OTHERWISE TO 43
      IF(IN(5)-6200000000)43,41,43
   41 F1=(1.+RATEI)**YRS
C  AMORT IS AN AMORTIZATION FACTOR THAT CONVERTS PLANT FIRST
C  COST TO A UNIFORM MONTHLY SERIES -- EQUAL MONTHLY PAYMENTS
      AMORT=(RATEI/(F1-1.))*(F1-PCT/100.)/12.
      WRITE(2,30)
   30 FORMAT(1H1, 41HFLOW  TERM   CD  B E T A  TIME  THICK * -
     1 50H---- COSTS, $ PER MILLION GALLONS ------ *   TOTAL/
     2 7X4HHEAD,9X5H4  -2,14X1H*,20X4HLAB+,19X1H*,4X4HCOST /
     3 52H GSFM   FT   PPM  10 FT      HR      IN  * TOTAL   1ST
     4 40H  OPER  MAIN  POWR  DIAT  BAKW *    $/MO/1H
     5 38(1H-),1H*,43(1H-),1H*,8(1H-))
      RETURN
C  IF COLUMN 6 CONTAINS S, STOP, OTHERWISE BRANCH TO 44
   43 IF(IN(5)-8200000000)44,42,44
C  VALUE IS A SUBROUTINE THAT DETERMINS VALUE OF NUMBER STORED
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C   IN IN ARRAY IN ALPHAMERIC NOTATION.  THE ARGUMENT SPECIFIES
C   WHICH ELEMENT OF IN ARRAY TO BEGIN WITH.  VALUE(1.0) IS THE
C   CARD INDEX NUMBER.  VALUE(10.0) IS THE FIRST NUMBER IN
C   COLUMNS 26-50 OF CARD.  VALUE(FACTR) IS THE FIRST NUMBER
C   FOLLOWING THE NUMBER JUST DETERMINED BY VALUE SUBROUTINE.
C   FACTR IN THIS USEAGE IS NOT THE BETA MULTIPLICATION FACTOR.
    44 INDEX=VALUE(1.0)
C   IF INDEX IS 1 TO 21, BRANCH TO STMT NUMBER = INDEX,
C   OTHERWISE IGNORE CARD AND READ THE NEXT CARD.  AFTER
C   NUMBERS ON CARD ARE DETERMINED, GO TO 45 AND READ NEXT CARD
       IF(INDEX)45,45,46
    46 IF(INDEX-21)47,47,45
    47 GO TO (1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,
     1 19,20,21),INDEX
     1 QMGD=VALUE(10.0)
       QMGMO=QMGD*30.4
       QGPM=QMGD*1000000.0/1440.0
       GO TO 45
     2 PCT=VALUE(10.0)
       GO TO 45
     3 EFF=VALUE(10.0)/100.
       GO TO 45
     4 RATEI=VALUE(10.0)/100.
       GO TO 45
     5 YRS=VALUE(10.0)
       GO TO 45
     6 CS=VALUE(10.0)
       GO TO 45
     7 XI=VALUE(10.0)
       GO TO 45
     8 FTEMP=VALUE(10.0)
C   VISCO IS SUBROUTINE THAT CONVERTS TEMP TO VIS
       VIS=VISCO(FTEMP)*3600.0
       GO TO 45
     9 W=VALUE(10.0)
       GO TO 45
    10 GP=VALUE(10.0)
       GO TO 45
    11 RS=VALUE(10.0)/24.0
C   RS=0 FOR FLAT SEPTUM
       GO TO 45
C   ELEMENTS 1 TO 4 OF B ARRAY CONTAIN COEFFICIENTS OF BETA
C   PREDICTION EQUATION
    12 B(1)=VALUE(10.0)
       B(2)=VALUE(FACTR)
       B(3)=VALUE(FACTR)
       B(4)=VALUE(FACTR)
       GO TO 45
C   FACTOR 8.02 CONVERTS GSFM TO FPH
    13 QI=VALUE(10.0)  *8.02
```

```
      QS=VALUE(FACTR) *8.02
C  IF QS=0, ONLY ONE VALUE OF UQ WILL BE USED IN CALCULATIONS.
C  THEREFORE, QS+QI MUST BE GREATER THAN QF.
      IF(QS)50,50,51
   51 QF=VALUE(FACTR) *8.02
      GO TO 45
   50 QS=1.
      QF=QI
      GO TO 45
   14 CDI=VALUE(10.0)
      CDS=VALUE(FACTR)
      IF(CDS)52,52,53
   53 CDF=VALUE(FACTR)
      GO TO 45
   52 CDS=1.
      CDF=CDI
      GO TO 45
   15 THI=VALUE(10.0)
      THS=VALUE(FACTR)
      IF(THS)54,54,55
   55 THF=VALUE(FACTR)
      GO TO 45
   54 THS=1.
      THF=THI
      GO TO 45
   16 CALL CDIAT(1)
      GO TO 45
   17 CALL CFUST(1)
      GO TO 45
   18 CALL CPOWR(1)
      GO TO 45
   19 CALL CLABR(1)
      GO TO 45
   20 CALL CBAKW(1)
      GO TO 45
   21 CALL CMAIN(1)
      GO TO 45
   42 STOP
      END


      FUNCTION VALUE(WHERE)
      DIMENSION IN(40)
      COMMON IN,FACTR
C
C  THIS SUBROUTINE DETERMINES VALUE OF NUMBER STARTING WITH
C  ELEMENT =WHERE= OF IN ARRAY BY USE OF VALU SUBROUTINE.
C  IF TERMINATION CHARACTER (CHARACTER FACTR-1 OF IN ARRAY
C  AFTER RETURNING FROM VALU) IS AN E, MEANS NUMBER JUST AFTER
```

```
C  E IS AN EXPONENT OF 10 FOR NUMBER JUST DETERMINED BY VALU.
C  E.G., NUMBER  1.3E8 ON CARD IS EQUAL TO 130000000.
C
      TEMP=VALU(WHERE)
      M=FACTR
      IF(IN(M-1)-6500000000)1,2,1
    1 VALUE=TEMP
      RETURN
    2 VALUE=TEMP*10.0**VALU(FACTR)
      RETURN
      END



      FUNCTION VALU (WHERE)
      DIMENSION IN(40)
      COMMON IN,FACTR
C
C  THIS SUBROUTINE CONVERTS NUMBER STORED IN IN ARRAY IN
C  ALPHAMERIC FORM TO NUMERIC FORM STARTING WITH ELEMENT WHERE
C  OF IN AND ENDING WITH TERMINATION CHARACTER.  TERMINATION
C  CHARACTERS FOR VALU ARE ANY CHARACTER OTHER THAN  +  -  .
C  OR A DIGIT.  IF NO DIGITS APPEAR BEFORE TERMINATION CHARAC-
C  TER, NUMBER IS TAKEN AS ZERO.
C
      M=WHERE
      VALU =0.0
      DO 40 K=M,34
      IF(IN(K)) 41,40,41
   40 CONTINUE
  122 RETURN
   41 SIGN=1.0
      NUMBR=0
      L=0
    1 M=K
      DO 22 K=M,34
      INK=IN(K)/100000000
A                 MSP  INK
   23 IF (INK-20) 24,22,24
   24 IF (INK-30) 27,25,27
   25 SIGN =-1.0
      GO TO 22
   27 IF (INK-15) 29,28,29
   28 L=1
      GO TO 22
   29 IF(INK/10-9)2,38,2
   38 NUMBR=NUMBR*10+INK-90
      IF(L)3,22,3
    3 L=L*10
   22 CONTINUE
  2 FACTR=K+1
    IF(L)17,17,18
 17 VALJ =SIGN*FLOATF(NUMBR)
    GO TO 5
 18 VALJ =SIGN*FLOATF(NUMBR)/FLOATF(L)
  5 RETURN
    END



      FUNCTION VISCO(C)
C
C  THIS SUBROUTINE CONVERTS FARENHEIT TEMPERATURE (ARGUMENT C)
C  TO KINEMATIC VISCOSITY IN  SQUARE FEET PER SECOND.
C
      VISCO=(286.405-SQRTF(53671.0-3.1027*(C-152.45)**2))*.0000001
      RETURN
      END



      SUBROUTINE DIEQS
      DIMENSION IN(40),B(4),ANS(13,10)
      COMMON IN,FACTR,UQ,QI,QS,QF,CD,CDI,CDS,CDF,TH,THI,THS,
     1 THF,XI,B,HP,HC,VIS,W,XLP,GP,G,PHI,RS,RO,TR,THICK,AREA,
     2 RF,SIGMA,CDE,CPO,CF,CL,CM,CB,QGPM,COPER,CTOTL,GW,AMORT,
     3 QMGMU,EFF,CS,BETA,ANS
C
C  THIS SUBROUTINE BY USE OF BETA PREDICTION EQUATION AND THE
C  DIATOMITE FILTRATION EQUATIONS FINDS AREA, BETA, LENGTH OF
C  FILTER RUN (TR), AND FILTER CAKE THICKNESS (THICK).
C  DILUTION EFFECT IS NEGLECTED IN THE CALCULATIONS.
C
C                DIATOMITE FILTRATION EQUATIONS
C  (ANY SEPTUM)    HP=UQ*XNU*XI*W/G
C  (CYLINDRICAL)   HC=RS*SIGMA*LOGF(1+RS*PHI*TR/RO**2)/PHI
C                  THICK=SQRTF(RO*RO+RS*PHI*TR)-RS
C  (FLAT)          HC=SIGMA*TR
C                  THICK=XLP+PHI*TR/2
C     WHERE  SIGMA=UQ*UQ*XNU*BETA*CD/G
C            PHI=2*UQ*GW*CD*(10)**(-6)/GP
C            RO=RS+XLP
C            XLP=W/GP
C            HC=TH-HP  (EQUIPMENT LOSSES IGNORED)
C
C  PRED IS SUBROUTINE FOR BETA PREDICTION
      BETA=PRED(FACTR)
      PHI=2.0*UQ* GW *CD*.000001/GP
      SIGMA=UQ*UQ*VIS*BETA*CD/G
      AREA=QGPM/(UQ/8.02)
      XLP=W/GP
      HP=UQ*VIS*XI*W/G
      HC=TH-HP
C   BRANCH TO 1 FOR FLAT SEPTUM, 2 FOR CYLINDRICAL.  (RS IS
C   STORED AS ZERO FOR FLAT SEPTUM)
      IF(RS)2,1,2
    1 TR=HC/SIGMA
      THICK=XLP+PHI*TR/2.0
      GO TO 3
    2 RO=RS+XLP
      TR=RO*RO*(EXPF(HC*PHI/(RS*SIGMA))-1.0)/(RS*PHI)
      THICK=SQRTF(RO*RO+RS*PHI*TR)-RS
    3 RETURN
      END



      FUNCTION PRED(DUMMY)
      DIMENSION IN(40),B(4),ANS(13,10)
      COMMON IN,FACTR,UQ,QI,QS,QF,CD,CDI,CDS,CDF,TH,THI,THS,
     1 THF,XI,B,HP,HC,VIS,W,XLP,GP,G,PHI,RS,RO,TR,THICK,AREA,
     2 RF,SIGMA,CDE,CPO,CF,CL,CM,CB,QGPM,COPER,CTOTL,GW,AMORT,
     3 QMGMO,EFF,CS,BETA,ANS
C
C   THIS SUBROUTINE COMPUTES BETA FROM THE PREDICTION EQUATION.
C   THE ARGUMENT DUMMY IS EQUAL TO FACTR WHEN PRED IS CALLED.
C
      PRED=DUMMY*10.0**B(1)*(CS/CD)**B(2)
      IF(B(3))1,2,1
    1 PRED=PRED*CD**B(3)
    2 IF(B(4))3,4,3
    3 PRED=PRED*XI**B(4)
    4 RETURN
      END



      SUBROUTINE COSTS
      DIMENSION IN(40),B(4),ANS(13,10)
      COMMON IN,FACTR,UQ,QI,QS,QF,CD,CDI,CDS,CDF,TH,THI,THS,
     1 THF,XI,B,HP,HC,VIS,W,XLP,GP,G,PHI,RS,RO,TR,THICK,AREA,
     2 RF,SIGMA,CDE,CPO,CF,CL,CM,CB,QGPM,COPER,CTOTL,GW,AMORT,
     3 QMGMO,EFF,CS,BETA,ANS
C
C   THIS SUBROUTINE CALLS THE INDIVIDUAL COST SUBROUTINES. ALL
C   THE COSTS ARE COMPUTED AS THE TOTAL FOR ONE MONTH.
C
C   ALL OF THE INPUT AND COST COMPUTATIONS FOR THE INDIVIDUAL
C   COSTS (FIRST, LABOR, MAINTENANCE, DIATOMITE, POWER, AND
C   BACKWASHING) ARE INCLUDED IN SEPARATE SUBROUTINES.  THESE
```

```
        SUBROUTINES HAVE ONE ARGUMENT THAT IS EITHER 1 FOR
      ESSARY INPUT FOR THE COMPUTATION OF THE PARTICULAR COST
C   OR 2 FOR THE ACTUAL COMPUTATION.  THESE ARGUMENTS ARE ALL
C   1 WHEN THE COST SUBROUTINES ARE CALLED IN SUBROUTINE READR
C   AND ARE ALL 2 WHEN CALLED FROM SUBROUTINE COSTS.  ALL COSTS
C   ARE COMPUTED ON A MONTHLY BASIS IN THE INDIVIDUAL ROUTINES.
C   THIS WAS DONE SO THAT CHANGES IN THE METHOD OF COMPUTING
C   ANY OF THE COSTS CAN BE MADE WITH THE LEAST DIFFICULTY --
C   I.E., BY CHANGING ONLY THE PARTICULAR SUBROUTINE.
C
      CALL CFOST(2)
      CALL CLABR(2)
      CALL CDIAT(2)
      CALL CMAIN(2)
      CALL CPOWR(2)
      CALL CBAKW(2)
      COPER=CDE+CM+CPO+CL+CB
      CTOTL=CF+COPER
      RETURN
      END



      SUBROUTINE STRES
      DIMENSION IN(40),B(4),ANS(13,10)
      COMMON IN,FACTR,UQ,QI,QS,QF,CD,CDI,CDS,CDF,TH,THI,THS,
     1 THF,XI,B,HP,HC,VIS,W,XLP,GP,G,PHI,RS,RO,TR,THICK,AREA,
     2 RF,SIGMA,CDE,CPO,CF,CL,CM,CB,QGPM,COPER,CTOTL,GW,AMORT,
     3 QMGMO,EFF,CS,BETA,ANS
C
C   THIS SUBROUTINE COMPARES CTOTL WITH THE TEN CHEAPEST VALUES
C   OF CTOTL COMPUTED THUS FAR (CTOTL IS STORED IN THE 7TH ROW
C   OF THE ANS ARRAY).  IF CTOTL IS LESS THAN ANY OF THE TEN
C   VALUES STORED, IT IS STORED IN ITS PROPER PLACE IN ANS.
C
      LIMIT=10
C   *  STORE IF ONE OF CHEAPEST 10
      DO 51 K=1,LIMIT
      IF(CTOTL-ANS(7,K))52,51,51
   51 CONTINUE
      RETURN
   52 J=LIMIT
   56 IF(J-K)54,54,53
   53 L=J-1
      DO 55 I=1,13
   55 ANS(I,J)=ANS(I,L)
      J=L
      GO TO 56
C   THE STMTS BELOW ILLUSTRATE WHAT IS STORED IN EACH OF THE 13
C   ROWS OF ANS FOR SUBSEQUENT OUTPUT.
```

```
   54 ANS(1,K)=UQ
      ANS(2,K)=TH
      ANS(3,K)=CD
      ANS(4,K)=BETA
      ANS(5,K)=TR
      ANS(6,K)=THICK
      ANS(7,K)=CTOTL
      ANS(8,K)=CF
      ANS(9,K)=COPER
      ANS(10,K)=CL+CM
      ANS(11,K)=CPO
      ANS(12,K)=CDE
      ANS(13,K)=CB
      RETURN
      END



      SUBROUTINE OUTPT
      DIMENSION IN(40),B(4),ANS(13,10)
      COMMON IN,FACTR,UQ,QI,QS,QF,CD,CDI,CDS,CDF,TH,THI,THS,
     1 THF,XI,B,HP,HC,VIS,W,XLP,GP,G,PHI,RS,RO,TR,THICK,AREA,
     2 RF,SIGMA,CDE,CPO,CF,CL,CM,CB,QGPM,COPER,CTOTL,GW,AMORT,
     3 QMGMO,EFF,CS,BETA,ANS
C
C   THIS SUBROUTINE PRINTS THE RESULTS FOR EACH OF THE 6 VALUES
C   OF FACTR.
C
C   *  I=FACTR CONVERTED TO PERCENT
      I=FACTR*100.0
      WRITE(2,1)I
    1 FORMAT(1H028X14HBETA INDEXES =I4,
     1 28H PERCENT OF PREDICTED VALUES)
      DO 2 I=1,10
C   *  UNIT FLOW RATE IS CONVERTED TO GSFM FOR OUTPUT
      ANS(1,I)=ANS(1,I)/8.02
C   *  J=TH, K=CD, L=BETA/10000
      J=ANS(2,I)
      K=ANS(3,I)
      L=ANS(4,I)/10000.0
C   *  CAKE THICKNESS IS CONVERTED TO INCHES FOR OUTPUT
      ANS(6,I)=ANS(6,I)*12.
C   *  M=TOTAL COST PER MONTH
      M=ANS(7,I)
C   *  MONTHLY COSTS ARE CONVERTED TO $/MG BY DIVIDING THE
C   *  MONTHLY COSTS BY THE QUANTITY OF WATER PRODUCED IN
C   *  ONE MONTH IN MG.
      DO 4 KK=7,13
    4 ANS(KK,I)=ANS(KK,I)/QMGMO
    2 WRITE(2,3)ANS(1,I),J,K,L,(ANS(N,I),N=5,13),M
    3 FORMAT(F5.2,I6,I5,I8,F7.1,F7.2,2H *,7F6.1,2H *,I8)
C  *  THE 7TH ROW OF ANS IS REINITIALIZED FOR THE NEXT VALUE
C  *  OF FACTR.
      BIG=1000000.**8.0
      DO 100 L=1,10
  100 ANS(7,L)=BIG
      RETURN
      END



      FUNCTION YINT(LIMIT,X,AX,AY)
      DIMENSION AX(50),AY(50)
C
C  THIS SUBROUTINE IS A LINEAR INTERPOLATION ROUTINE.  AY IS
C  THE DEPENDENT VARIABLE ARRAY, AX IS THE INDEPENDENT
C  VARIABLE ARRAY, LIMIT IS THE NUMBER OF ELEMENTS IN ARRAYS
C  AX AND AY, X IS THE VALUE OF X FOR WHICH A CORRESPONDING
C  VALUE OF Y IS DESIRED.  YINT IS THE INTERPOLATED VALUE OF Y
C
      IF(X-AX(1))6,6,5
    6 YINT=AY(1)
      RETURN
    5 DO 1 I=2,LIMIT
      IF(X-AX(I))2,3,1
    1 CONTINUE
    3 YINT=AY(LIMIT)
      GO TO 4
    2 J=I-1
      YINT=AY(J)+(X-AX(J))*(AY(I)-AY(J))/(AX(I)-AX(J))
    4 RETURN
      END



      SUBROUTINE CFUST(L)
      DIMENSION IN(40),B(4),ANS(13,10)
      COMMON IN,FACTR,UO,QI,QS,QF,CD,CDI,CDS,CDF,TH,THI,THS,
     1 THF,XI,B,HP,HC,VIS,W,XLP,GP,G,PHI,RS,RO,TR,THICK,AREA,
     2 RF,SIGMA,CDE,CPO,CF,CL,CM,CB,CGPM,COPER,CTOTL,GW,AMORT,
     3 QMGMO,EFF,CS,BETA,ANS
      DIMENSION A(50),Z(50)
C  A=LOG(AREA), Z=LOG(FIRST COST PER UNIT AREA,$/SF)
C
C  CFUST IS THE SUBROUTINE WHERE FIRST COST IS COMPUTED.
C  BRANCH TO STMNT 1 FOR INPUT, STMNT 2 FOR COMPUTATION
C  POINTS FROM THE CURVE OF FIRST COST ($/SF) VERSUS AREA (LOG
C  SCALE) ARE READ IN BY THIS SUBROUTINE.  THE POINTS CHOSEN
C  FOR INPUT SHOULD BE SUCH THAT LINEAR INTERPOLATION DOES NOT
C  LEAD TO APPRECIABLE ERROR.  DATA CARD FORMATS FOR INPUT OF
```

```
C  FIRST COST INFORMATION SHOULD BE AS FOLLOWS
C
C  17 FIRST COST                      AREA      $/SF
C                                      100       225
C                                      200       160
C                                      ---       ---
C                                      ---       ---
C     *                              25000        85
C
C  THE NUMBERS WRITTEN IN ABOVE ARE ONLY FOR ILLUSTRATION.
C  ACTUAL NUMBERS ENTERED WILL DEPEND ON THE PARTICULAR FIRST
C  COST-AREA CURVE.  AS MANY AS 50 POINTS FROM THE CURVE MAY
C  BE READ IN.  THE POINTS MUST BE ENTERED SO THAT THE VALUES
C  OF AREA ARE IN ASCENDING ORDER.  CAUTION -- THE LAST DATA
C  POINT CARD MUST HAVE SOME CHARACTER PUNCHED IN COLUMN 6,
C  PREFERRABLY AN ASTERISK * .  COLUMN 6 OF ALL OTHER DATA
C  POINT CARDS MUST BE BLANK.
C
C  FOR EACH DATA POINT READ IN, LOG(AREA) IS STORED IN ITS
C  PROPER POSITION IN ARRAY A, LOG(FIRST COST PER UNIT AREA)
C  IS STORED IN THE CORRSPONDING POSITION IN ARRAY Z.
C  FOR A GIVEN AREA, LOG(AREA) IS COMPUTED AND ITS CORRES-
C  PONDING FIRST COST PER UNIT AREA IS FOUND BY TAKING THE
C  ANILOG OF THE INTERPOLATED VALUE OF LOG(FIRST COST PER UNIT
C  AREA.  THE AMORTIZED FIRST COST IS THEN COMPUTED AS THE
C  FIRST COST PER UNIT AREA TIMES THE AREA TIMES AMORT TIMES A
C  RATE FACTOR (RF).
C
C  FOR PROPER USE OF POPO, THE FIRST COST-AREA CURVE SHOULD BE
C  DETERMINED FOR A PATICULAR TYPE OF INSTALLATION AND A KNOWN
C  DESIGN FLOW.  IN THIS CASE, THE PLANT FIRST COSTS ESTIMATED
C  FOR THE PURPOSE OF DETERMINING THE FIRST COST-AREA CURVE
C  WOULD ALL BE ON THE BASIS OF THE DESIGN FLOW.  IN SUCH A
C  CASE, THE RATE FACTOR SHOULD BE UNITY BECAUSE THE EFFECT OF
C  FLOW RATE IS INCLUDED IN THE ORIGINAL COST ESTIMATES.
C  HOWEVER, IF THE PLANT FIRST COSTS ARE ALL ESTIMATED ON THE
C  BASIS OF A UNIT FLOW RATE OF 1 GSFM, THEN PLANT FIRST COSTS
C  DETERMINED FROM THE RESULTING FIRST COST-AREA CURVE WOULD
C  BE TOO LOW FOR A PLANT FILTERING AT A UNIT FLOW RATE
C  GREATER THAN 1 GSFM BECAUSE PUMPS AND PIPING, BODY FEEDERS,
C  ETC. WOULD HAVE TO BE LARGER TO HANDLE THE LARGER FLOW.  IN
C  THIS CASE, AN ARBITRARY RATE FACTR IS INTRODUCED TO COMPEN-
C  SATE.  IN DETERMINING THIS RATE FACTOR, IT IS ASSUMED THAT
C  THE FIRST COST OF THE PLANT IS INCREASED BY 20 PERCENT FOR
C  EACH GSFM THAT THE UNIT FLOW RATE EXCEEDS 1 GSFM.  THIS
C  RATE FACTOR IS COMPUTED AS    RF=1.+(UQ-8.)/40.
C
      IF(L-1)1,1,2
    1 DO 3 I=1,50
      READ(1,40)(IN(J),J=1,40)
      WRITE(2,40)(IN(J),J=1,40)
   40 FORMAT(1X5A1,A4,3A5,25A1,6A5)
      TEMP=VALUE(10.0)
      A(I)=LOGF(TEMP)
      TEMP=VALUE(FACTR)
      Z(I)=LOGF(TEMP)
      IF(IN(5))4,3,4
    3 CONTINUE
    4 LIMIT=I
      RETURN
    2 TEMP=LOGF(AREA)
      RF=1.+(UQ-8.)/40.
      TEMP=YINT(LIMIT,TEMP,A(1),Z(1))
      CF=EXPF(TEMP)*AREA*AMORT*RF
      RETURN
      END



      SUBROUTINE CLABR(L)
      DIMENSION IN(40),B(4),ANS(13,10)
      COMMON IN,FACTR,UQ,QI,QS,QF,CD,CDI,CDS,CDF,TH,THI,THS,
     1 THF,XI,B,HP,HC,VIS,W,XLP,GP,G,PHI,RS,RO,TR,THICK,AREA,
     2 RF,SIGMA,CDE,CPO,CF,CL,CM,CB,QGPM,COPER,CTOTL,GW,AMORT,
     3 QMGMO,EFF,CS,BETA,ANS
      DIMENSION A(50),Z(50)
C  A=LOG(AREA), Z=LOG(COST OF MAIN+LABOR IN $/MO.SF)
C
C  CLABR IS THE SUBROUTINE WHERE LABOR COST IS COMPUTED.
C  HOWEVER, FOR THE PRESENT TIME, BOTH LABOR AND MAINTENANCE
C  COST ARE COMPUTED TOGETHER IN THIS SUBROUTINE.  INPUT AND
C  COMPUTATION ARE DONE BY THIS SUBROUTINE EXACTLY THE SAME AS
C  IN SUBROUTINE CFOST.  THE ONLY DIFFERENCE IS THE ABSENCE OF
C  THE AMORTIZATION FACTOR (AMORT) IN THIS SUBROUTINE.
C  DATA ÇARD FORMATS FOR LABOR AND MAINTENANCE COSTS INFOR-
C  MATION INPUT SHOULD BE AS FOLLOWS
C
C  19 LABOR COST                 AREA      $/SF PER MONTH
C                                 100        2.00
C                                 200        1.15
C                                 ---         ---
C                                 ---         ---
C    *                           4500        0.30
C
C     CAUTION -- ASTERISK (OR SOME CHARACTER) MUST BE PUNCHED
C                IN COLUMN 6 OF LAST DATA POINT CARD.
C
      IF(L-1)1,1,2
    1 DO 3 I=1,50
      READ(1,40)(IN(J),J=1,40)
```

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```
      WRITE(2,40)(IN(J),J=1,40)
   40 FORMAT(1X5A1,A4,3A5,25A1,6A5)
      TEMP=VALUE(10.0)
      A(I)=LOGF(TEMP)
      TEMP=VALUE(FACTR)
      Z(I)=LOGF(TEMP)
      IF(IN(5))4,3,4
    3 CONTINUE
    4 LIMIT=I
      RETURN
    2 TEMP=LOGF(AREA)
      TEMP=YINT(LIMIT,TEMP,A(1),Z(1))
      CL=EXPF(TEMP)*AREA*RF
      RETURN
      END



      SUBROUTINE CDIAT(L)
      DIMENSION IN(40),B(4),ANS(13,10)
      COMMON IN,FACTR,UQ,QI,QS,QF,CD,CDI,CDS,CDF,TH,THI,THS,
     1 THF,XI,B,HP,HC,VIS,W,XLP,GP,G,PHI,RS,RO,TR,THICK,AREA,
     2 RF,SIGMA,CDE,CPO,CF,CL,CM,CB,QGPM,COPER,CTOTL,GW,AMORT,
     3 QMGMO,EFF,CS,BETA,ANS
C
C   CDIAT IS WHERE DIATOMITE COST IS COMPUTED.  IT IS COMPUTED
C   BY MULTIPLYING THE UNIT COST PER TON TIMES THE NUMBER OF
C   TONS USED PER MONTH FOR PRECOAT AND BODY FEED.  THE NUMBER
C   OF TONS OF PRECOAT AND BODY FEED NEEDED PER MONTH ARE
C           PREDE=W*AREA*24*30.4/(TR*2000)
C           BFDE=CD*QMGMO*8.33/2000
C
C   FOR INPUT, L=1 AND THE UNIT COST OF DIATOMITE IS DETERMINED
C   FROM THE DIATOMITE COST CARD (INDEX=16).  THE FORMAT FOR
C   THIS CARD SHOULD BE AS FOLLOWS
C
C   16 DIATOMITE COST                     100   $/TON
C
C   THE VALUE OF 100 IS SHOWN FOR ILLUSTRATION.  ACTUAL VALUE
C   DEPENDS ON PARTICULAR CASE.
C
      IF(L-1)1,1,2
    1 UCDE=VALUE(10.0)
      F1=  24.*30.4/2000.
      F2=8.33/2000.
      RETURN
    2 PREDE=F1*W*AREA/TR
      BFDE=F2*CD*QMGMO
       CDE=UCDE*(PREDE+BFDE)
      RETURN
      END


      SUBROUTINE CPOWR(L)
      DIMENSION IN(40),B(4),ANS(13,10)
      COMMON IN,FACTR,UQ,QI,QS,QF,CD,CDI,CDS,CDF,TH,THI,THS,
     1 THF,XI,B,HP,HC,VIS,W,XLP,GP,G,PHI,RS,RO,TR,THICK,AREA,
     2 RF,SIGMA,CDE,CPO,CF,CL,CM,CB,QGPM,COPER,CTOTL,GW,AMORT,
     3 QMGMO,EFF,CS,BETA,ANS
C
C   POWER COST IS COMPUTED IN THIS SUBROUTINE.  IT IS COMPUTED
C   ON THE BASIS OF THE DESIGN FLOW RATE BEING PUMPED CON-
C   TINUOUSLY AT THE TERMINAL HEAD LOSS.  A SINGLE VALUE OF
C   CENTS PER KWH IS USED.  AN OVERALL EFFICIENCY OF ENERGY
C   CONVERSION (EFF) IS ASSUMED.  THE MONTHLY ENERGY USE IS
C   COMPUTED AS
C      QGPM*GW*TH*.746*24*30.4/(449*550*EFF)
C   THE MONTHLY COST IS FOUND BY MULTIPLYING THE COST PER KWH
C   (EQUIVALENT TO VALUE(10.)/100. DETERMINED FROM THE POWER
C   COST CARD) TIMES THE KWH OF ENERGY USED IN ONE MONTH.  THE
C   FORMAT FOR THE POWER COST CARD (INDEX=18) SHOULD BE
C
C   18 POWER COST                     1.5  CENTS/KWH
C
C   A VALUE OF 1.5 CENTS PER KWH HAS BEEN INDICATED FOR
C   DEMONSTRATION.  ACTUAL VALUE WOULD DEPEND ON THE PARTICULAR
C   CASE.
C
      IF(L-1)1,1,2
    1 CONST=(VALUE(10.)/100.)*GW*.746*24.*30.4/(449.*550.)
      RETURN
    2 CPO=CONST*TH*QGPM/EFF
      RETURN
      END


      SUBROUTINE CMAIN(L)
      DIMENSION IN(40),B(4),ANS(13,10)
      COMMON IN,FACTR,UQ,QI,QS,QF,CD,CDI,CDS,CDF,TH,THI,THS,
     1 THF,XI,B,HP,HC,VIS,W,XLP,GP,G,PHI,RS,RO,TR,THICK,AREA,
     2 RF,SIGMA,CDE,CPO,CF,CL,CM,CB,QGPM,COPER,CTOTL,GW,AMORT,
     3 QMGMO,EFF,CS,BETA,ANS
C
C   CMAIN IS THE SUBROUTINE WHERE MAINTENANCE COST WOULD
C   ORDINARILY BE COMPUTED.  HOWEVER, IN THE PRESENT FORM OF
C   THE PROGRAM, MAINTENANCE COST IS INCLUDED WITH LABOR COST,
C   AND THEREFORE, COMPUTED IN CLABR.  THE PRESENT CMAIN
C   SUBROUTINE PERFORMS NO MAINTENANCE COST COMPUTATIONS. IT IS
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C  INCLUDED JUST IN CASE IT BECOMES DESIREABLE TO SEPARATE
C  LABOR AND MAINTENANCE COSTS COMPUTATION IN THE FUTURE.  A
C  MAINTENANCE COST CARD (CARD INDEX 21) IS NOT NEEDED FOR THE
C  PROGRAM IN ITS PRESENT FORM.
C
C  *  L=1 FOR INPUT AND 2 FOR COMPUTATION
C  *  NO INPUT FOR PRESENT FORM OF SUBROUTINE
C  *  CM SET = TO 0 BECAUSE IT IS ADDED TO THE OTHER COSTS IN
C  *  SUBROUTINE COSTS.  CM IS INCLUDED IN CL AND THEREFORE CM
C  *  MUST BE ZEROED.
      IF(L-1)1,1,2
    1 RETURN
    2 CM=0.0
      RETURN
      END



      SUBROUTINE CBAKW(L)
      DIMENSION IN(40),B(4),ANS(13,10)
      COMMON IN,FACTR,QQ,QI,QS,QF,CD,CDI,CDS,CDF,TH,THI,THS,
     1 THF,XI,B,HP,HC,VIS,W,XLP,GP,G,PHI,RS,RO,TR,THICK,AREA,
     2 RF,SIGMA,CDE,CPO,CF,CL,CM,CB,QGPM,COPER,CTOTL,GW,AMORT,
     3 QMGMO,EFF,CS,BETA,ANS
C
C  BACKWASHING COSTS ARE COMPUTED IN THIS SUBROUTINE.  DURING
C  FILTERING OPERATION, THE QUANTITY OF WATER USED FOR WASHING
C  THE FILTERS AND THE QUANTITY OF WATER THAT WOULD HAVE BEEN
C  FILTERED DURING FILTER DOWN TIME (FOR WASHING) MUST ALSO BE
C  FILTERED IF COST COMPARISONS ARE TO BE BASED ON THE SAME
C  QUANTITY OF FINISHED WATER LEAVING THE PLANT.  THUS, THE
C  UNIT FLOW RATE WOULD HAVE TO BE INCREASED SLIGHTLY.  IT IS
C  ASSUMED THAT FILTERING BAKWASH WATER INCREASES CDE, CL, CM,
C  CB PROPORTIONATELY, AND THAT FILTERING WATER NOT FILTERED
C  WHEN WASHING INCREASES CL, CM, CDE, CB PROPORTIONATELY. THE
C  RESPECTIVE FRACTIONAL INCREASES ARE TAKEN AS THE RATIO OF
C  THE BACKWASH WATER USED PER MONTH TO THE FINISHED WATER
C  PRODUCED PER MONTH (BWMGM/QMGMO) AND THE RATIO OF BACKWASH
C  DOWN TIME TO LENGTH OF FILTER RUN (BWT/TR).  THE FORMAT FOR
C  THE BACKWASH COST CARD (INDEX=20) SHOULD BE
C
C  20 BACKWASH COST            10, 30      GAL/SF, MIN
C
C  VALUES OF 10 GAL/SF AND 30 MIN HAVE BEEN INDICATED FOR
C  DEMONSTRATION.
C
C                 CBAKW NOMENCLATURE
C   BWGSF=BACKWASH WATER NEEDED     BWMGM=BACKWASH WATER NEEDED
C      IN GAL/SF                       IN MG/MO
C   CB1=COST OF BACKWASH WATER      CB2=COST PER MONTH FOR
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C        PER MONTH                         FILTERING WATER NOT
C     BWT=BACKWASH DOWN TIME, HR           FILTERED DURING DOWD
C                                          TIME FOR WASHING
      IF(L-1)1,1,2
    1 BWGSF=VALUE(10.0)
      F1=    BWGSF*24.*30.4*.000001
      BWT=VALUE(FACTR)/60.
      RETURN
    2 BWMGM=F1*AREA/TR
      F3=BWMGM/QMGMO
      F4=BWT/TR
      CB1=F3*(CDE+CL+CM+CPO)
      CB2=F4*(CL+CM+CDE+CB1)
      CB=F3*(CDE+CL+CM+CPO+CB1+CB2)+F4*(CL+CM+CDE+CB1+CB2)
      RETURN
      END
```